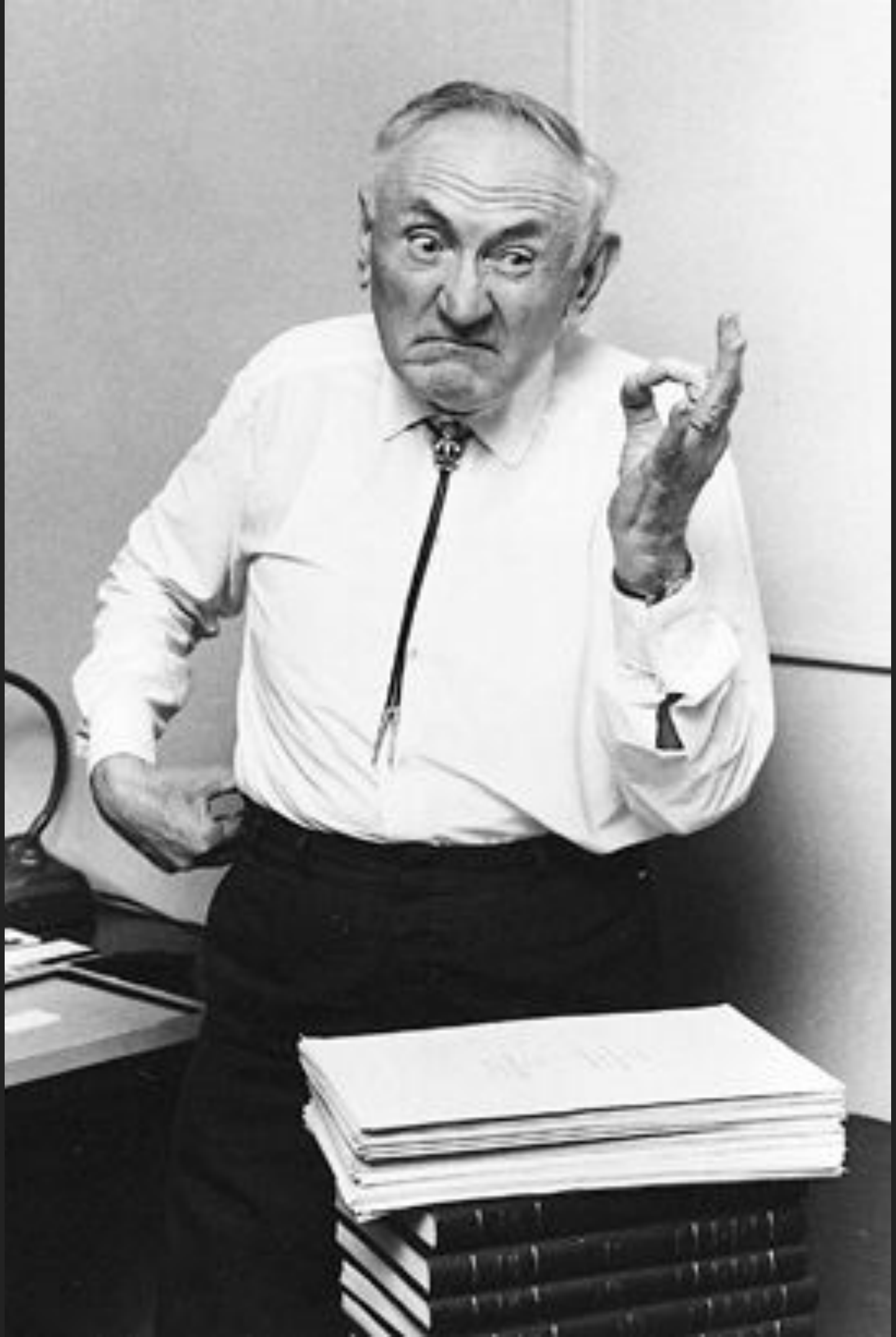
TEMPLE UNIVERSITY

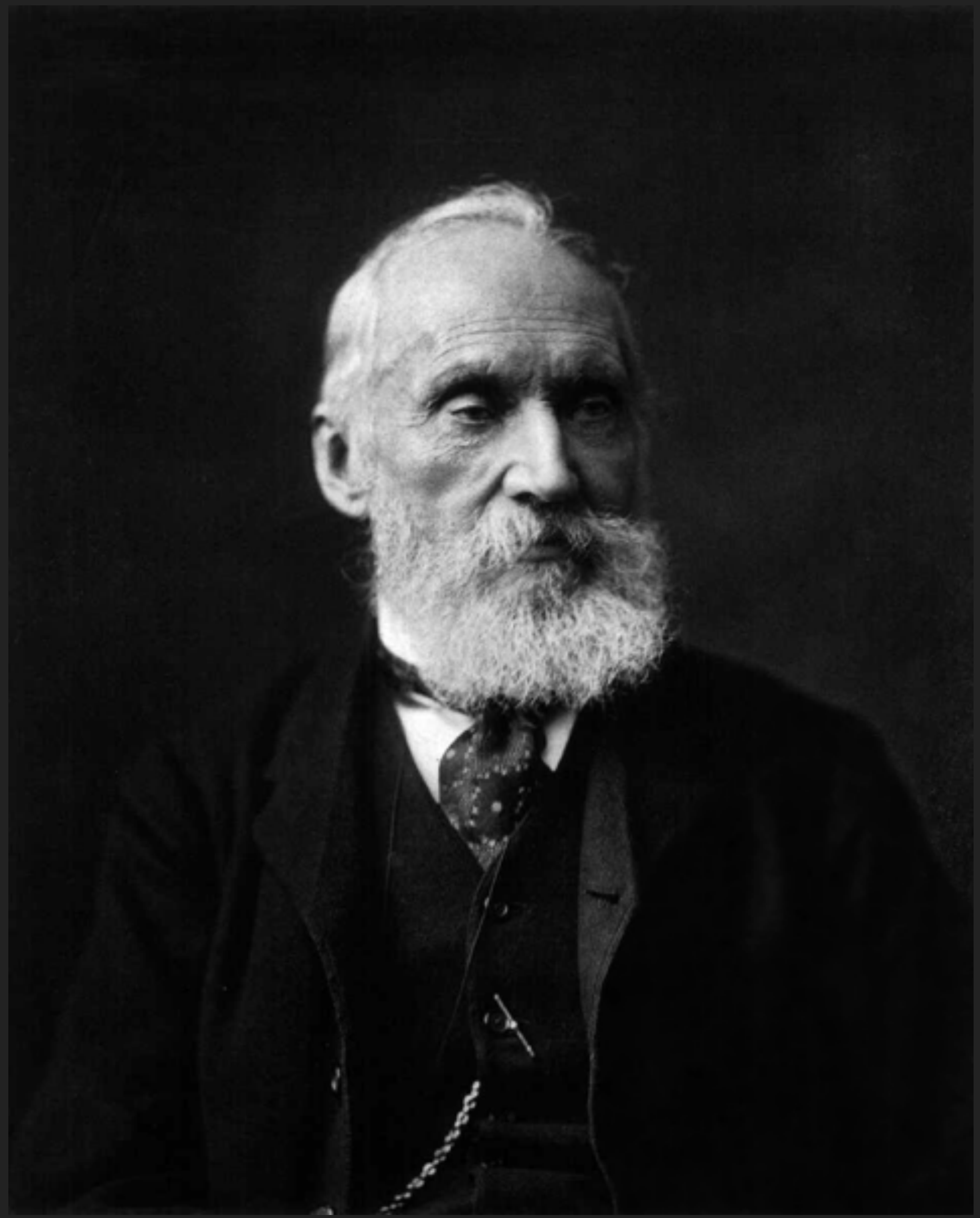
DARKSIDE

ANDREW W WATSON

THE PAST, PRESENT, AND FUTURE OF DARK MATTER

awwatson.com

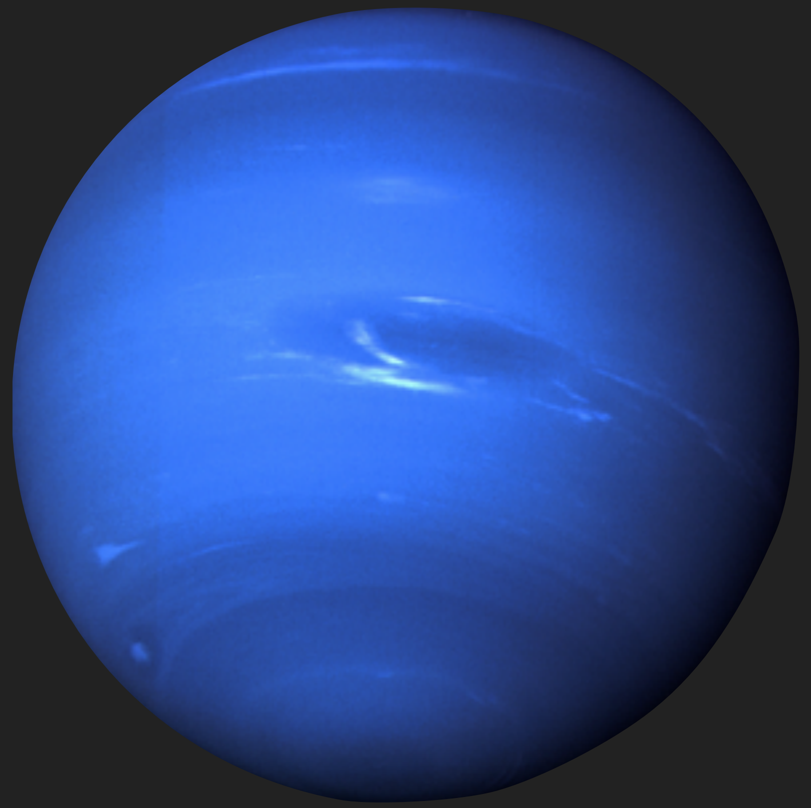


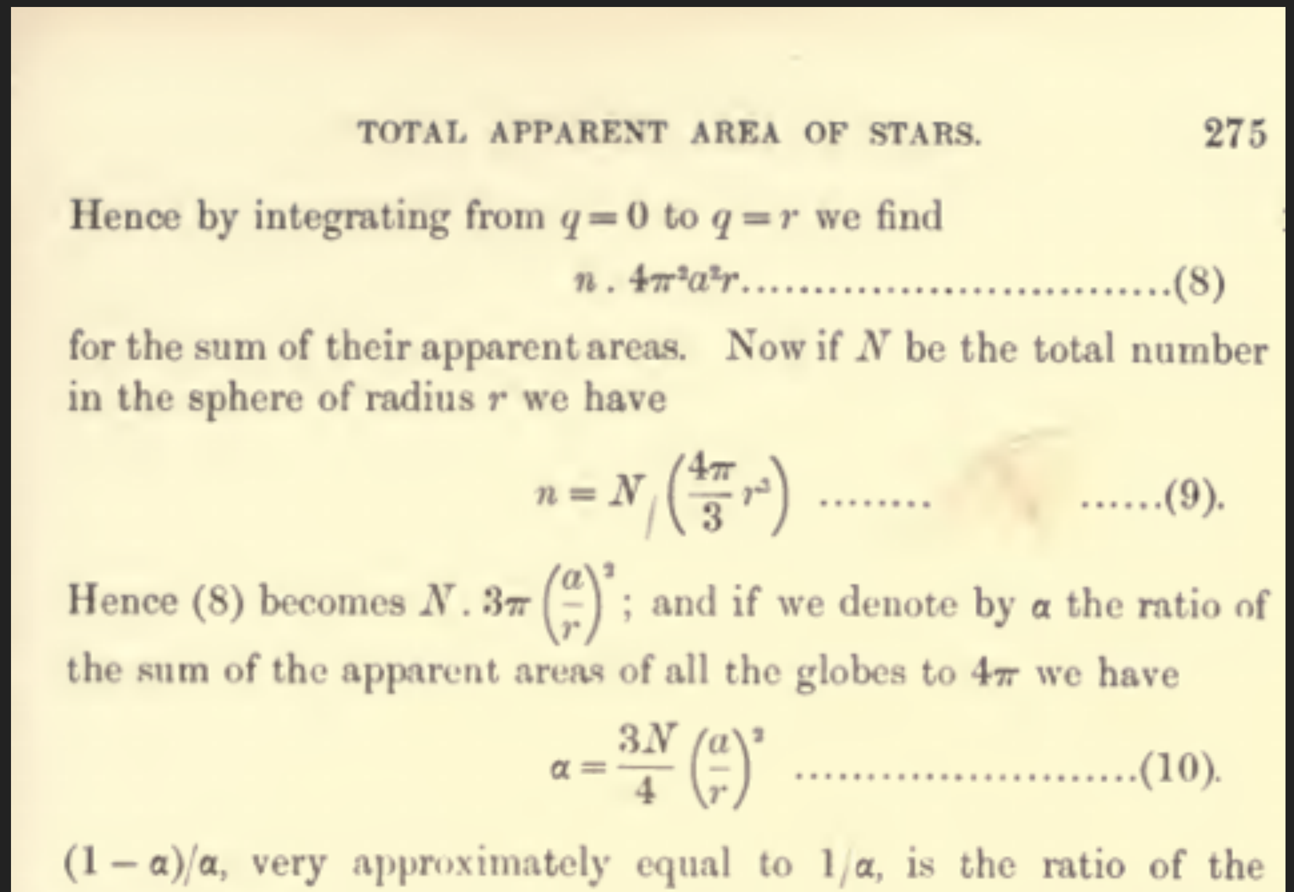


Urbain Le Verrier
11 Mar 1811 - 23 Sep 1877

Lord Kelvin
26 Jun 1824 - 17 Dec 1907

Henri Poincaré
29 Apr 1854 - 17 Jul 1912





TOTAL APPARENT AREA OF STARS. 275

Hence by integrating from $q=0$ to $q=r$ we find

$$n \,.\, 4\pi^2 a^2 r \quad \ldots\ldots (8)$$

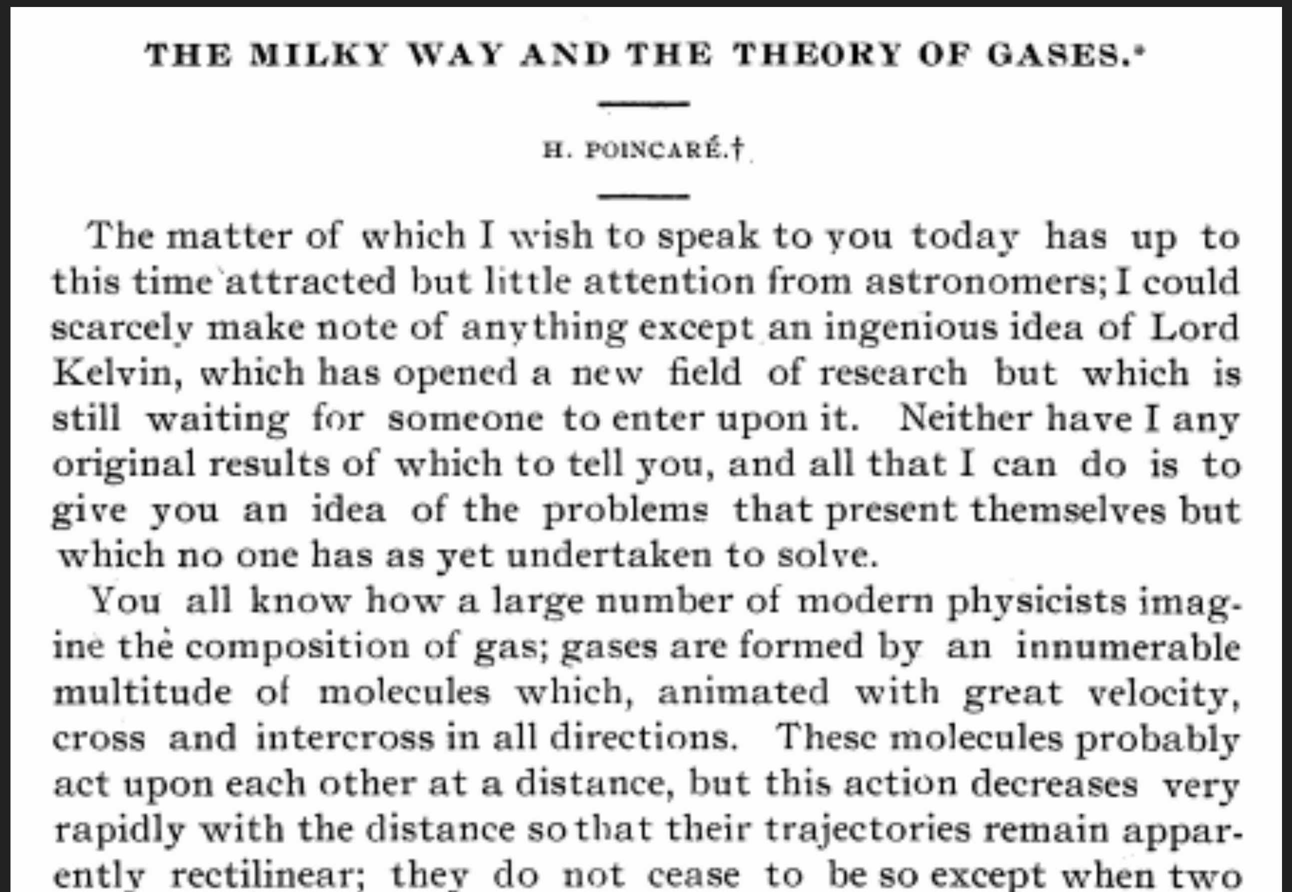
for the sum of their apparent areas. Now if N be the total number in the sphere of radius r we have

$$n = N / \left(\frac{4\pi}{3} r^3\right) \quad \ldots\ldots (9).$$

Hence (8) becomes $N \,.\, 3\pi \left(\frac{a}{r}\right)^2$; and if we denote by α the ratio of the sum of the apparent areas of all the globes to 4π we have

$$\alpha = \frac{3N}{4} \left(\frac{a}{r}\right)^2 \quad \ldots\ldots (10).$$

$(1-\alpha)/\alpha$, very approximately equal to $1/\alpha$, is the ratio of the



THE MILKY WAY AND THE THEORY OF GASES.*

H. POINCARÉ.†

The matter of which I wish to speak to you today has up to this time attracted but little attention from astronomers; I could scarcely make note of anything except an ingenious idea of Lord Kelvin, which has opened a new field of research but which is still waiting for someone to enter upon it. Neither have I any original results of which to tell you, and all that I can do is to give you an idea of the problems that present themselves but which no one has as yet undertaken to solve.

You all know how a large number of modern physicists imagine the composition of gas; gases are formed by an innumerable multitude of molecules which, animated with great velocity, cross and intercross in all directions. These molecules probably act upon each other at a distance, but this action decreases very rapidly with the distance so that their trajectories remain apparently rectilinear; they do not cease to be so except when two

ZWICKY & THE COMA CLUSTER

- virial theorem

$$2\langle T\rangle = n\langle V_{\mathrm{TOT}}\rangle$$

- mass-to-light (γ = M/L) ratios
- Coma Cluster: γ ~ 500
- need more evidence!

The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

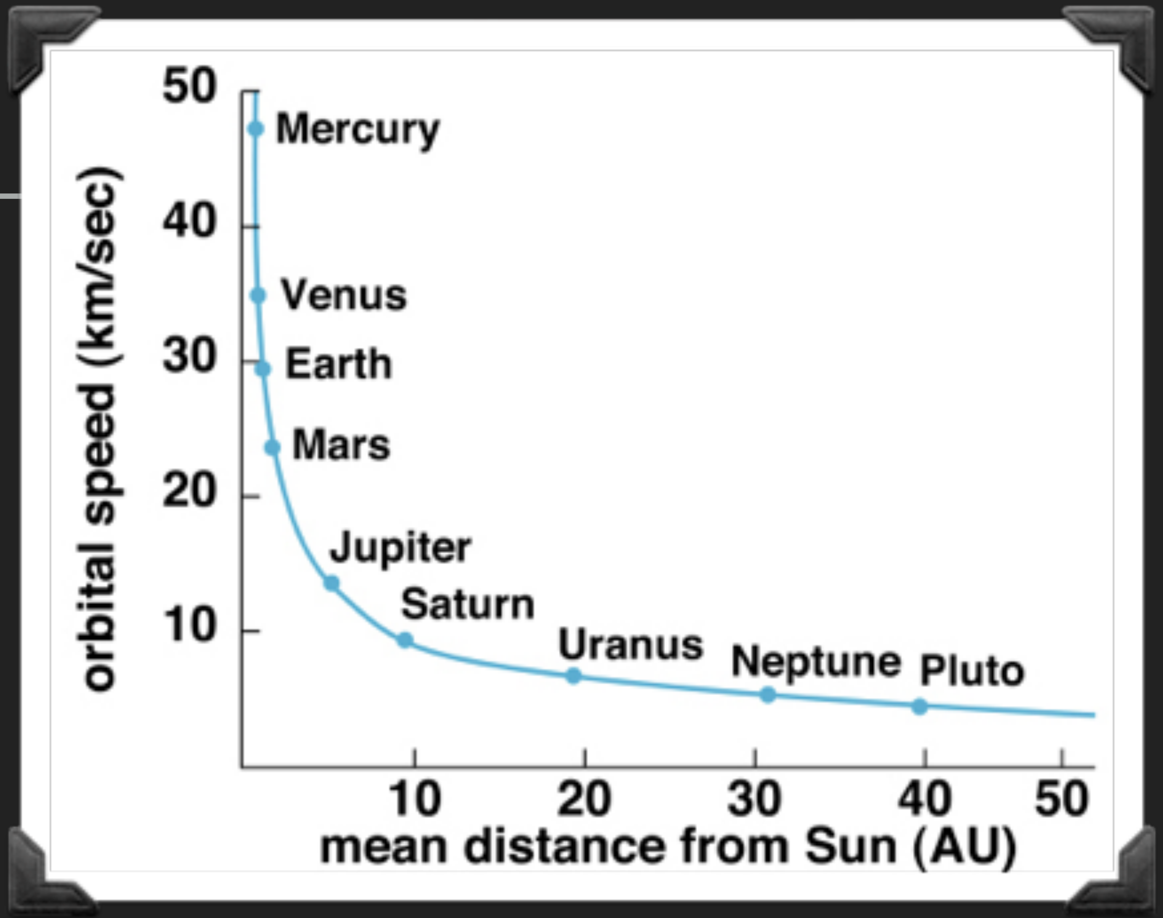
$$\overline{M} > 9 \times 10^{43}\ \mathrm{gr} = 4.5 \times 10^{10}\ M_\odot\,. \qquad (36)$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathcal{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According to (36), the conversion factor γ from luminosity to mass for nebulae in the Coma cluster would be of the order

$$\gamma = 500\,, \qquad (37)$$

as compared with about $\gamma' = 3$ for the local Kapteyn stellar system. This discrepancy is so great that a further analysis of the problem is in order. Parts of the following discussion were published several

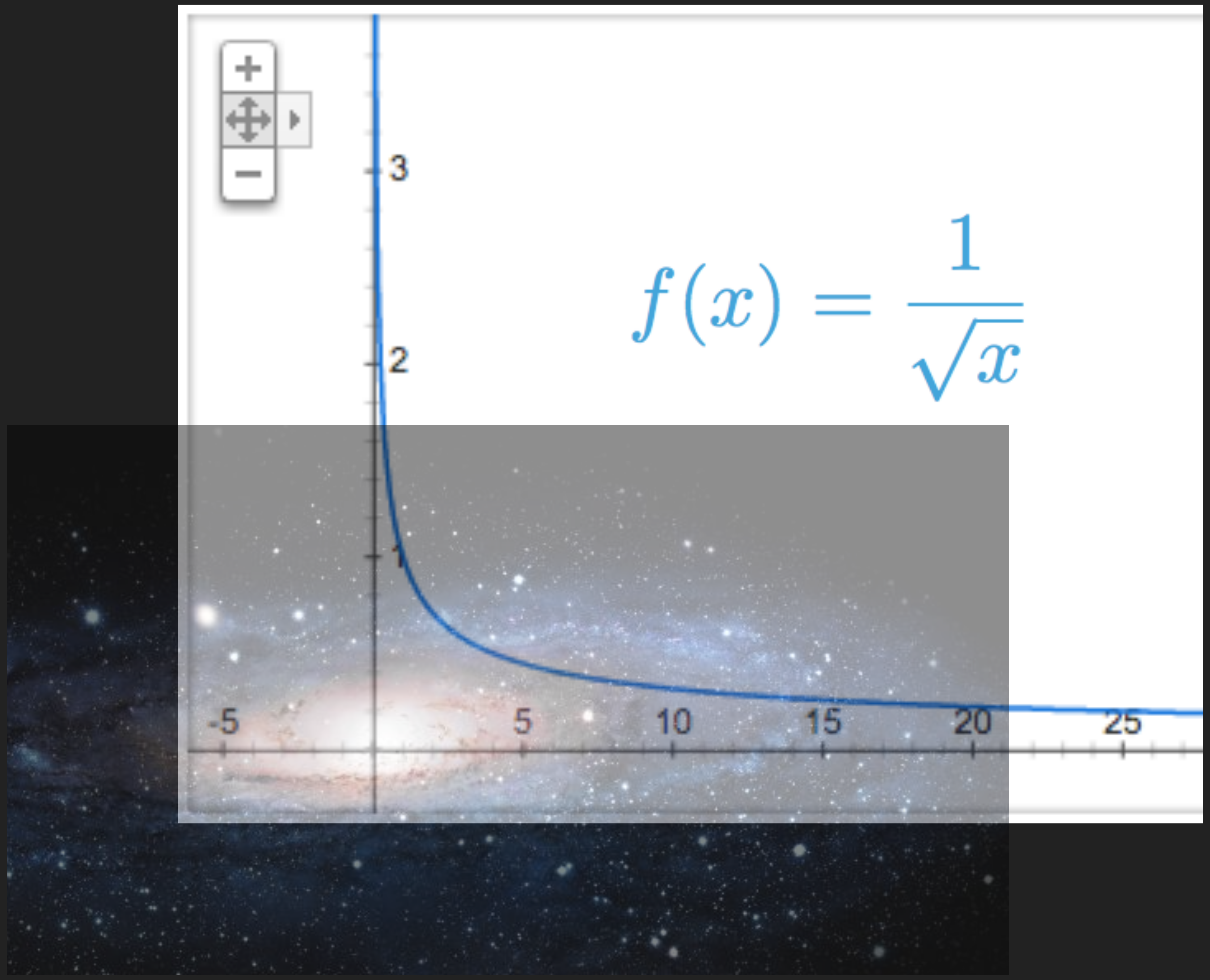
GALACTIC ROTATION CURVES (1/2)



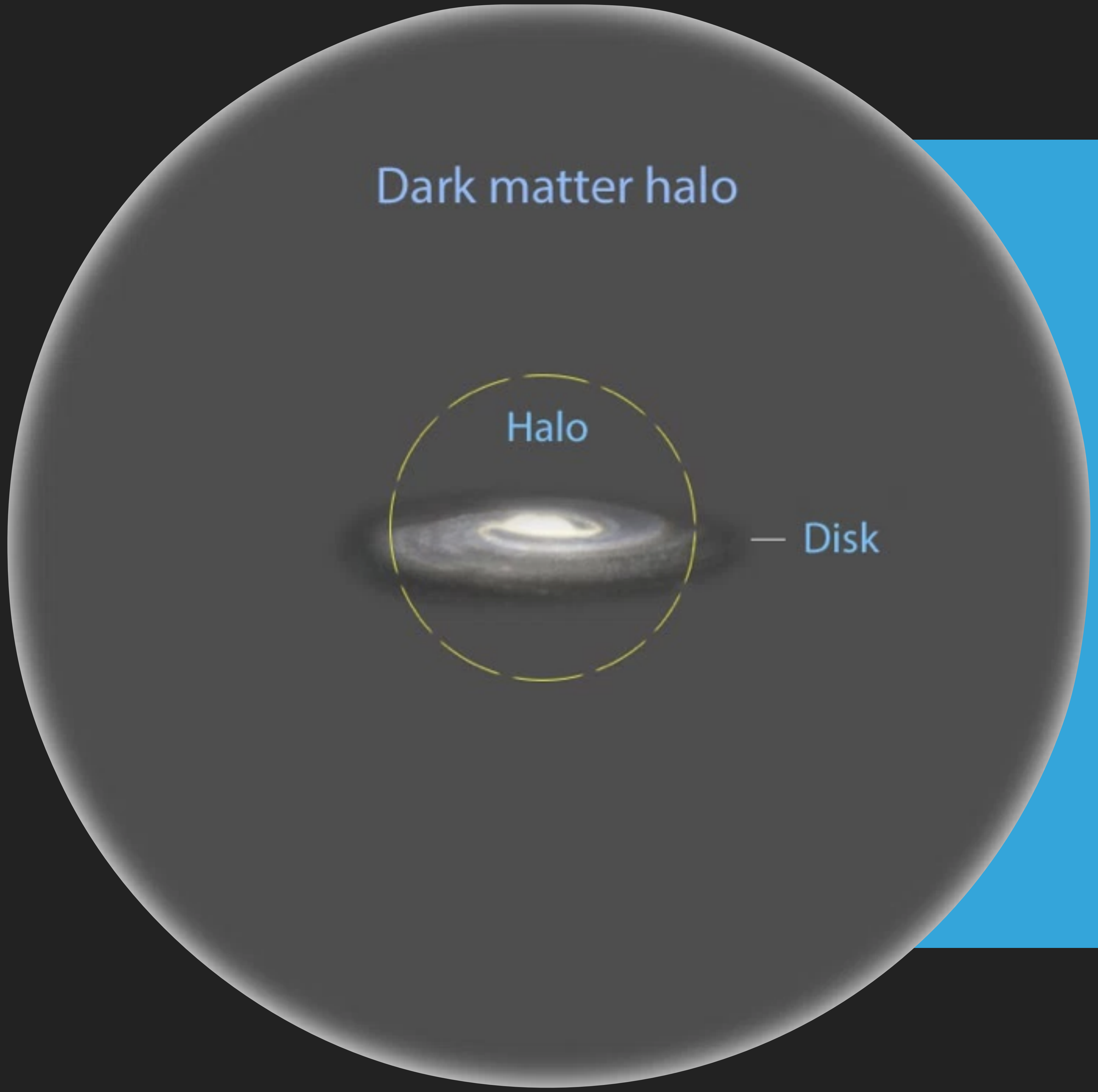
$$|F| = ma = m\frac{(v(r))^2}{r} = G\frac{mM(r)}{r^2}$$

$$\longrightarrow v(r) = \sqrt{\frac{GM(r)}{r}}$$

$$\lim_{r \gtrsim r_{\text{lum}}} v(r) = \sqrt{\frac{GM_{\text{lum}}}{r}} = \frac{const.}{\sqrt{r}}$$



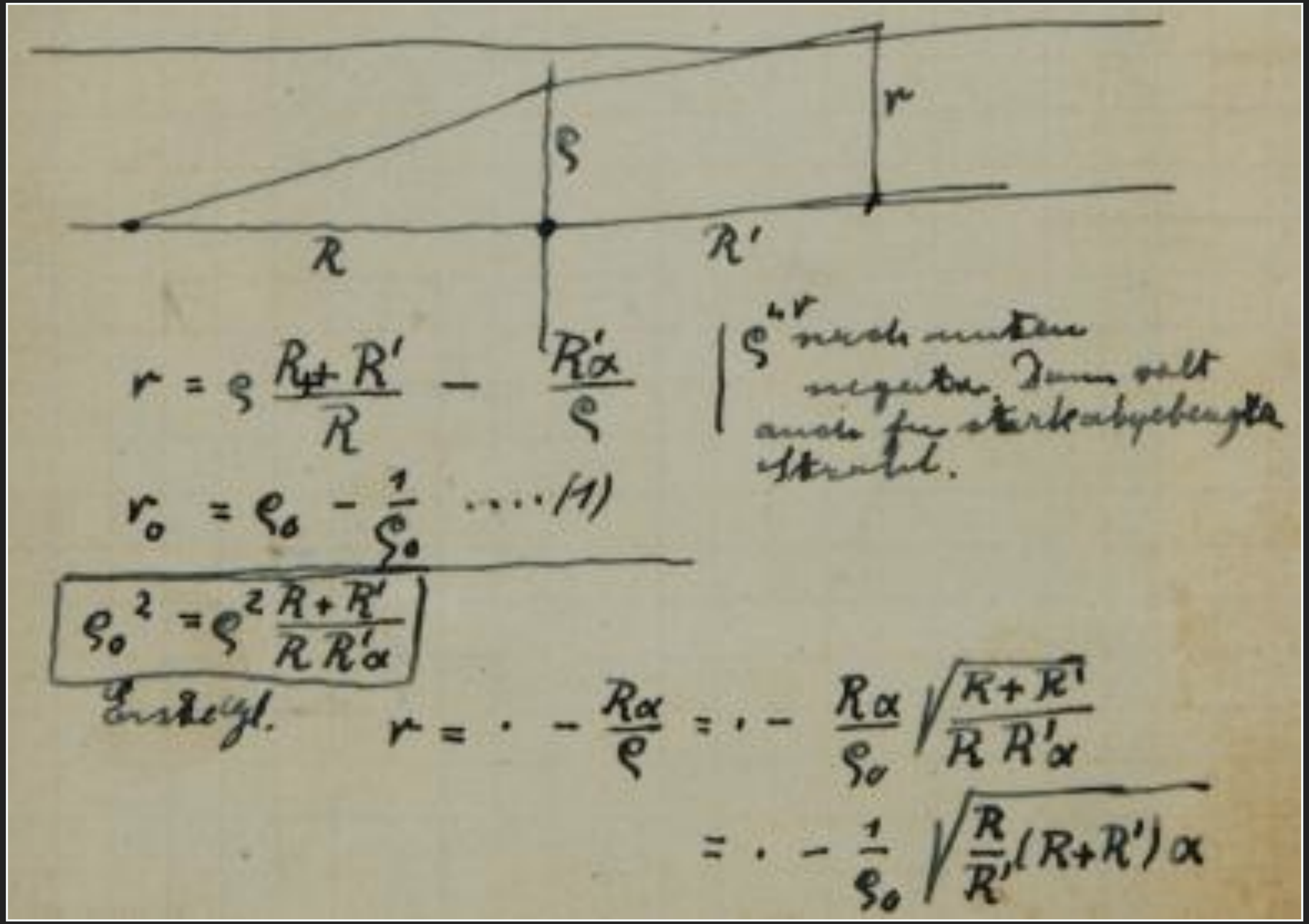
GALACTIC ROTATION CURVES (2/2)

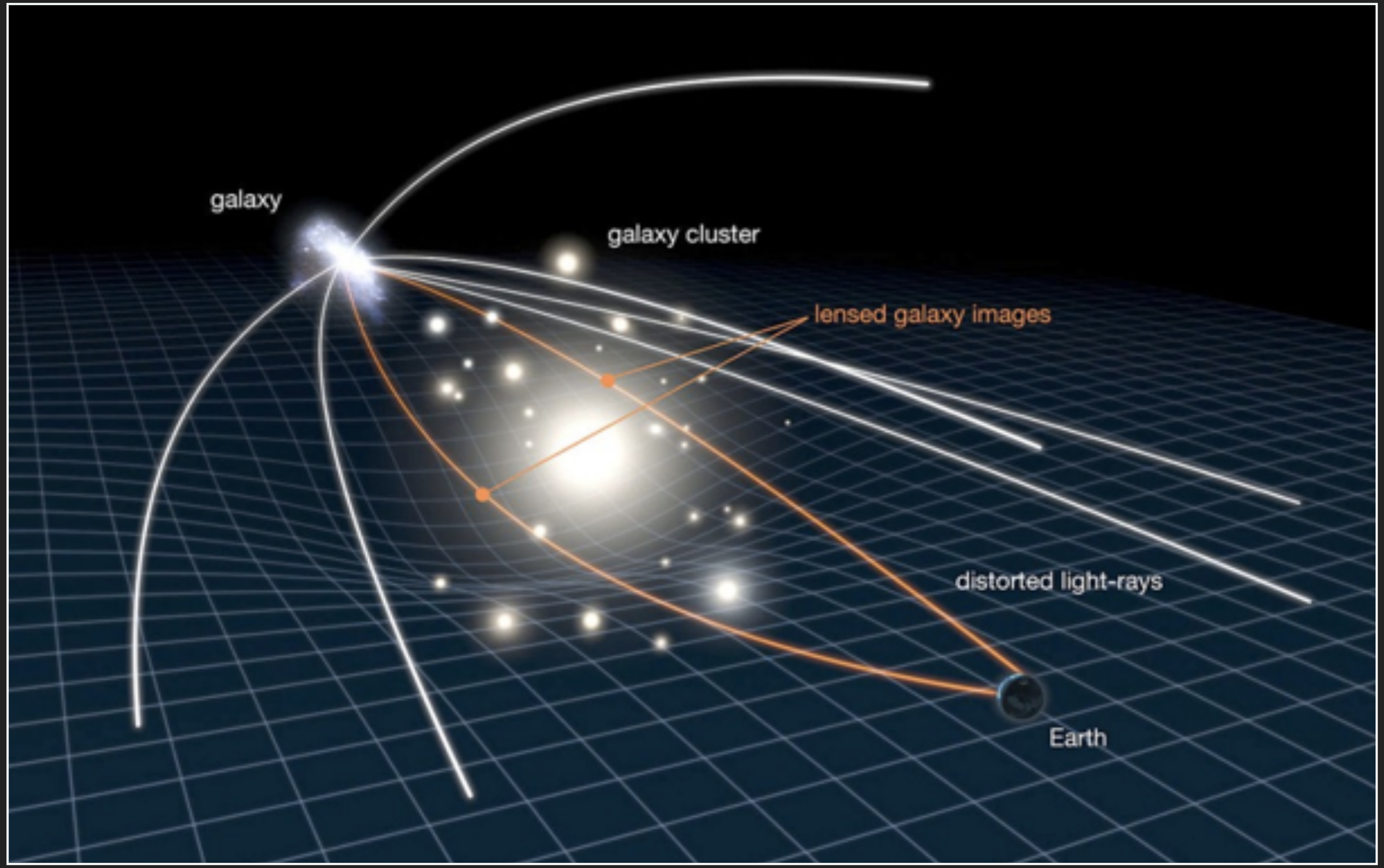


"IF [THE DATA] ARE CORRECT, THEN THERE MUST BE IN THESE GALAXIES ADDITIONAL MATTER WHICH IS UNDETECTED, EITHER OPTICALLY OR AT 21 CM. ITS MASS MUST BE AT LEAST AS LARGE AS THE MASS OF THE DETECTED GALAXY, AND ITS DISTRIBUTION MUST BE QUITE DIFFERENT FROM THE EXPONENTIAL DISTRIBUTION WHICH HOLDS FOR THE OPTICAL GALAXY."

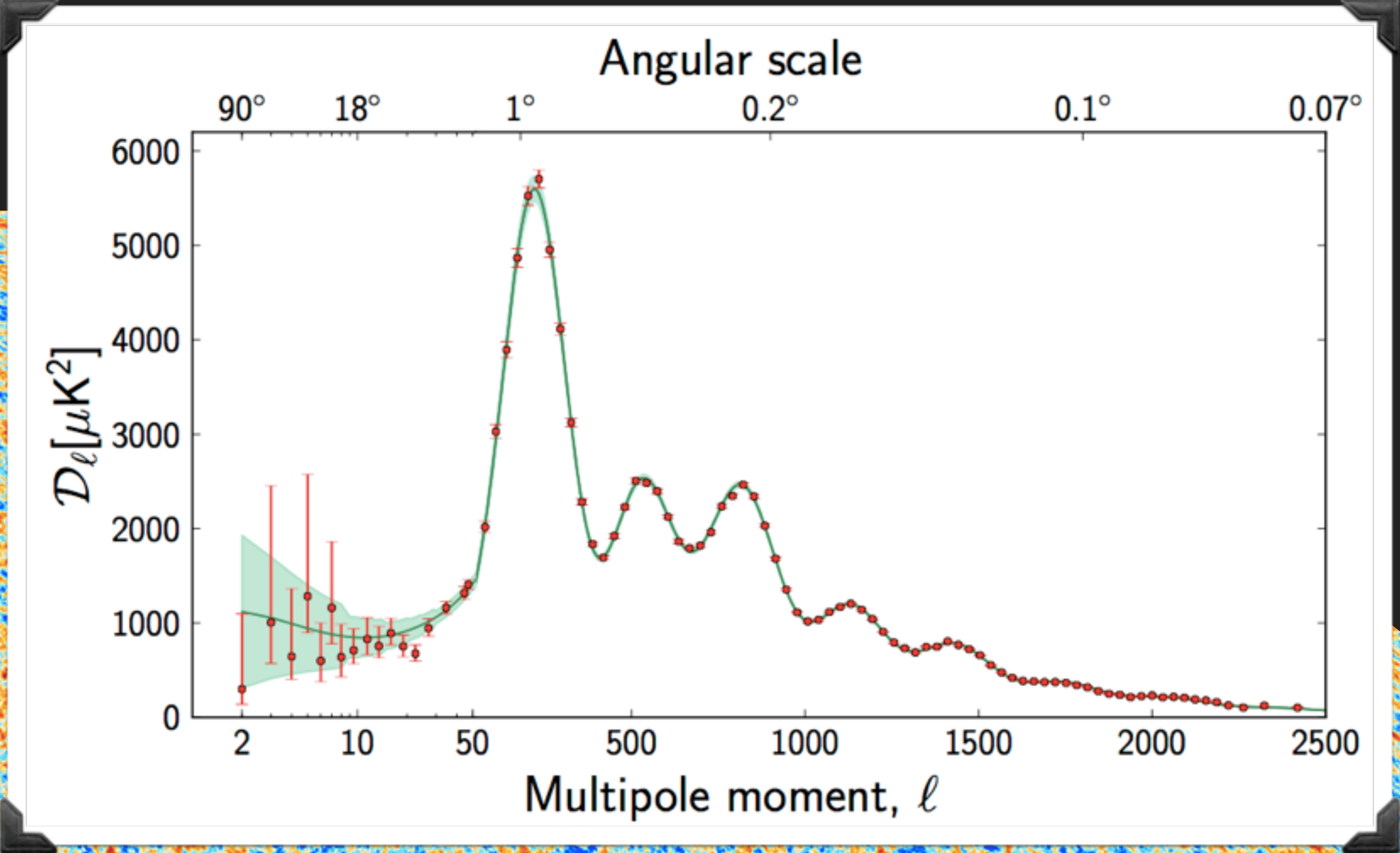
Ken Freeman, 1970

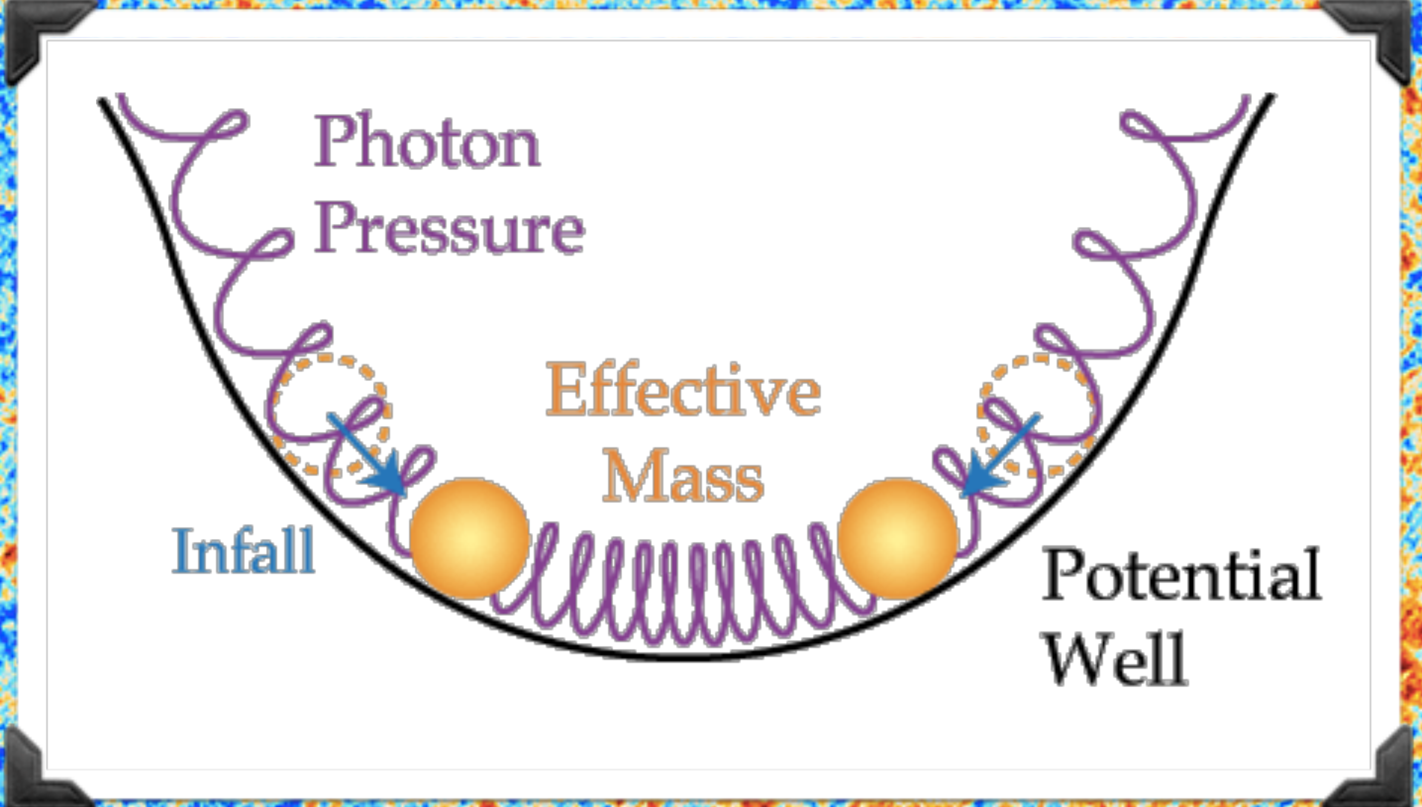
GRAVITATIONAL LENSING





THE CMB AND BAO





PROPERTIES / CHARACTERISTICS OF DARK MATTER

- existence inferred through large-scale gravitational effects
- must be electrically neutral
- much more prevalent than "regular" baryonic matter
  - CMB/BAO studies give precise concentrations
- must be stable over the lifetime of the universe

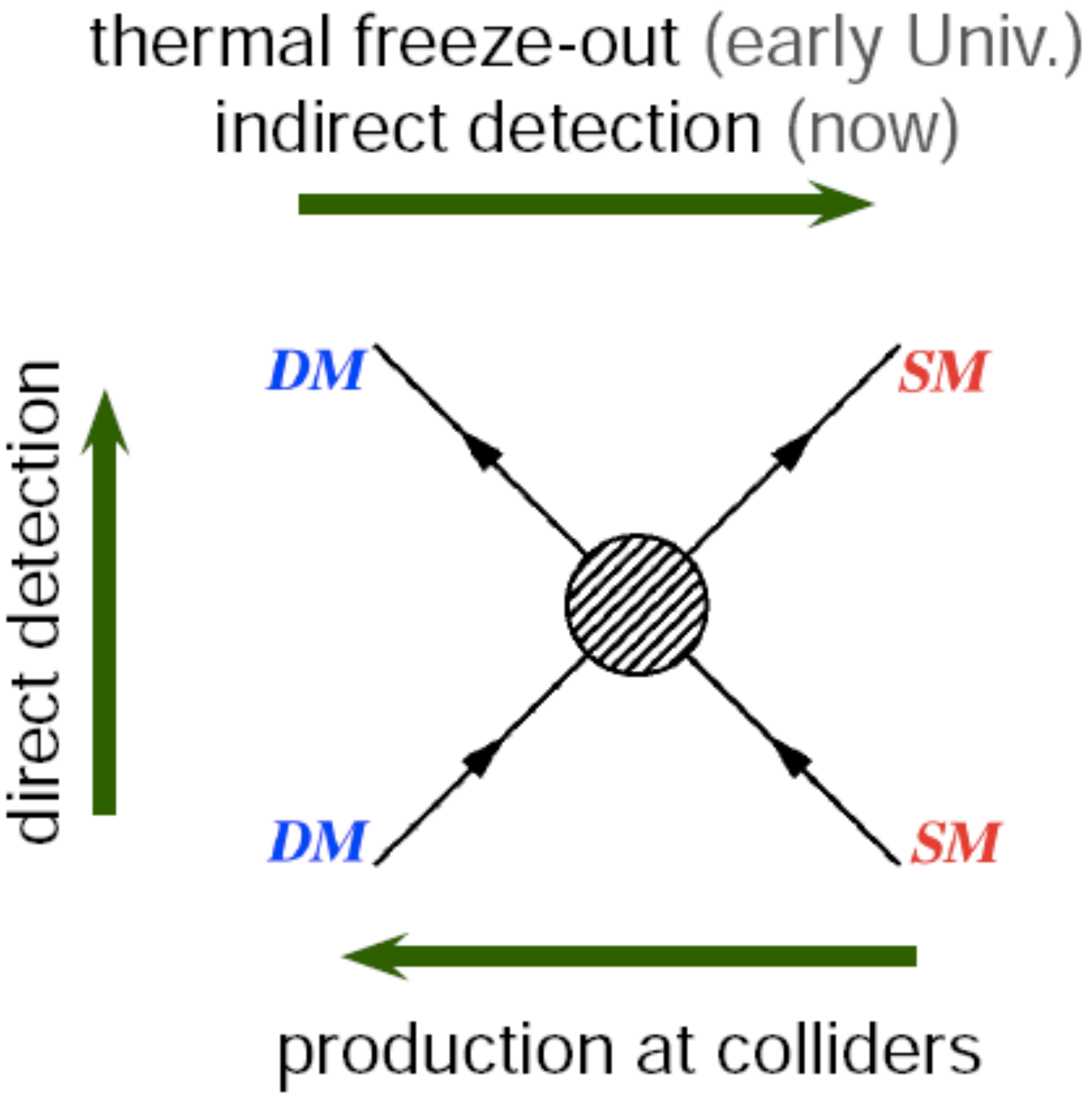
PAST AND PRESENT DARK MATTER CANDIDATES

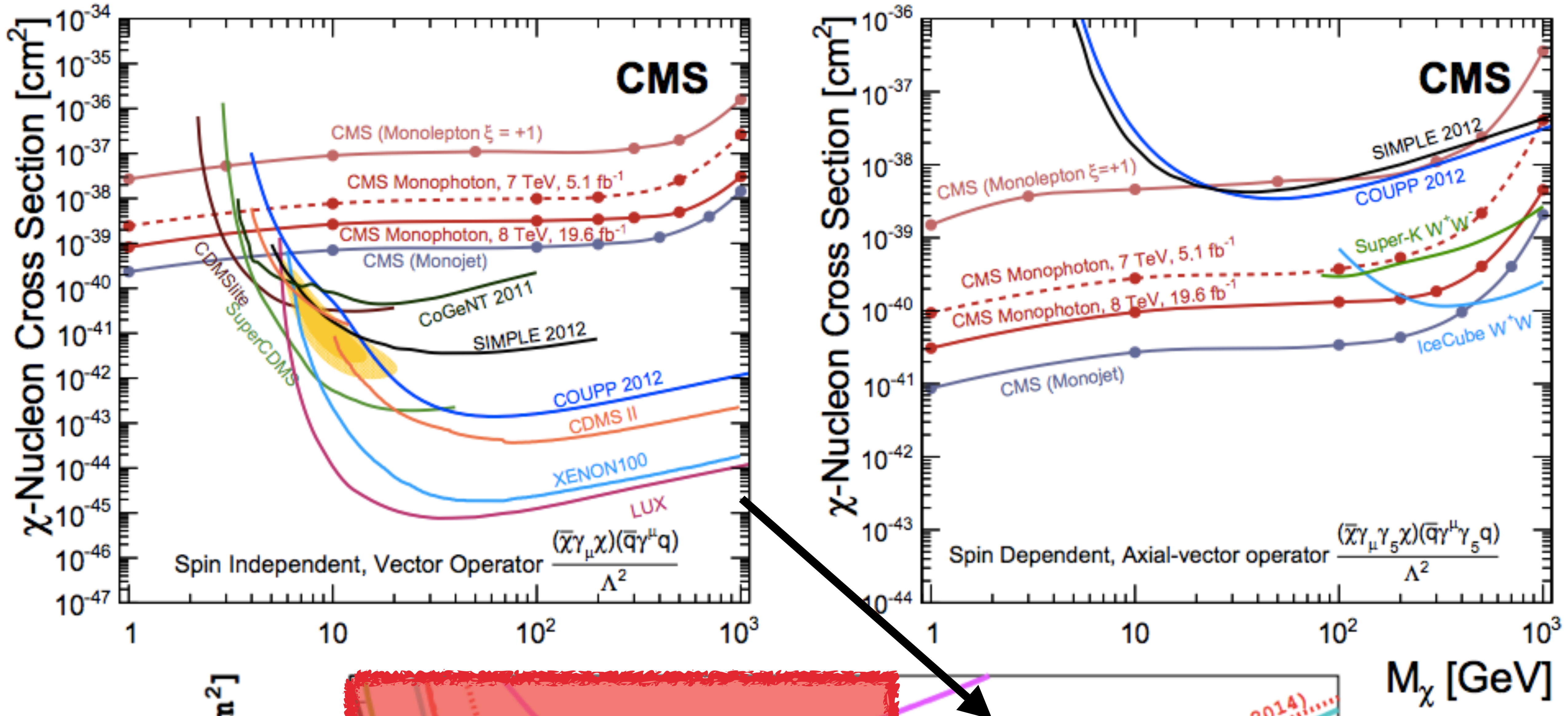
less likely

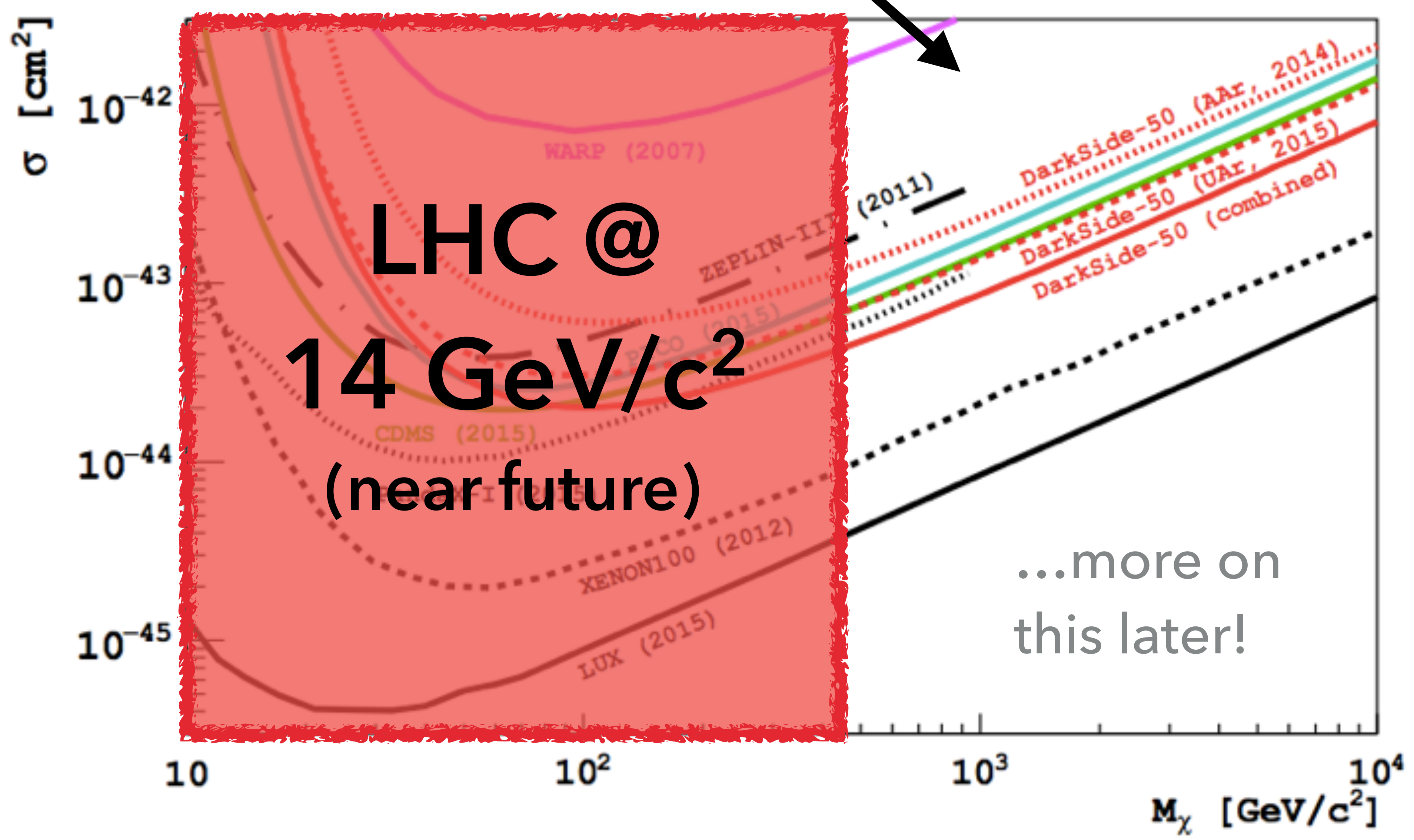
- **normal baryonic matter**: gas, dust, "meteoric" matter
- **MACHOs**: rogue planets, neutron stars, white dwarfs, etc.
- **black holes**: primordial black holes only
- **neutrinos**: not heavy enough!
  - **sterile neutrinos**: R-handed neutrinos; still looking for these!
- **axions**: could solve both strong CP and dark matter
- **supersymmetric particles**: "the WIMP miracle"

more likely

DIRECT DETECTION VS. INDIRECT DETECTION VS. CREATION







THE DARKSIDE COLLABORATION

48 Universities, Laboratories and Organizations from 12 countries

Timeline:

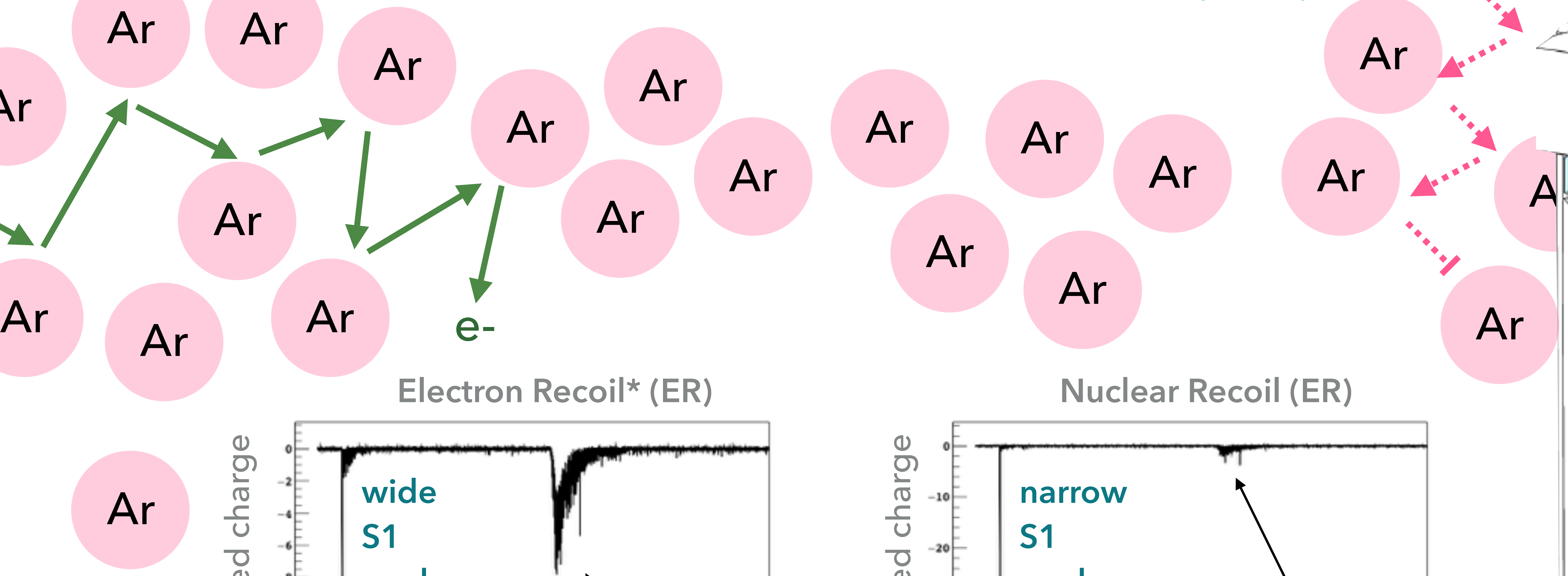
2011 - 2013
"DS-10"
10kg active volume prototype

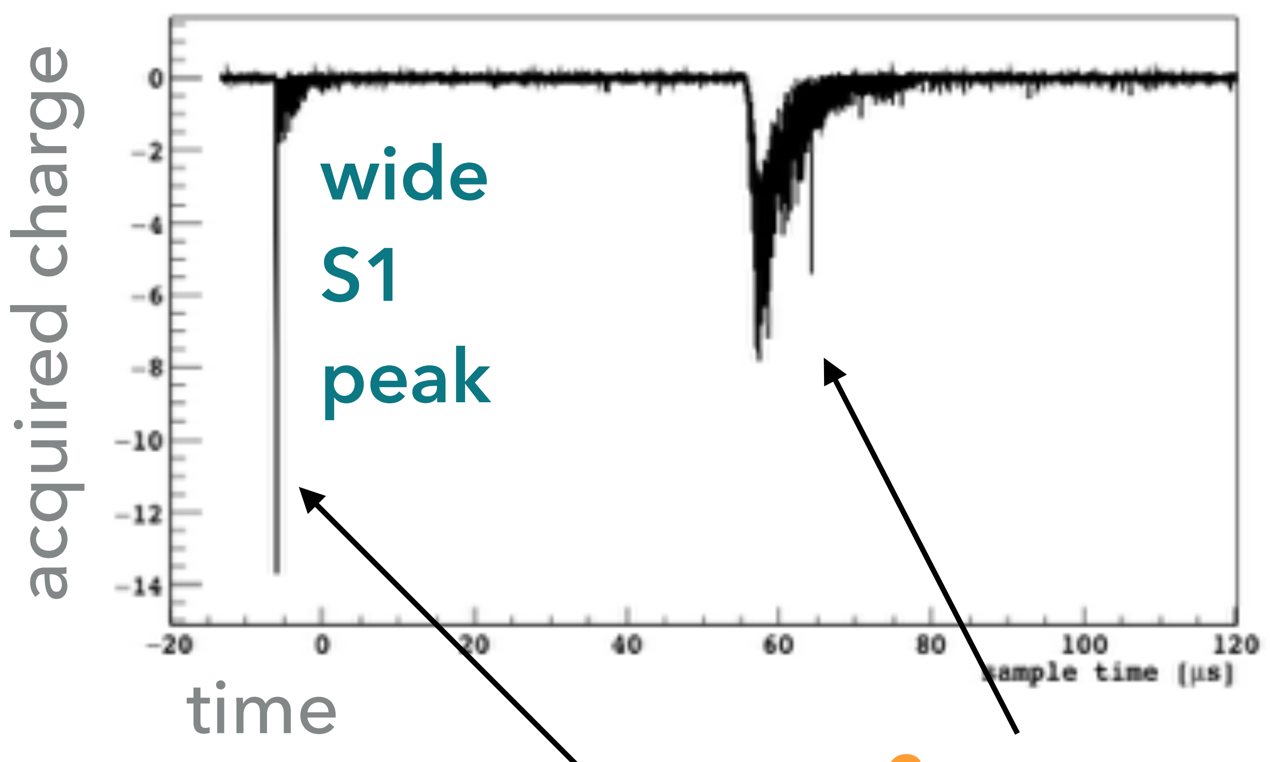
2013 - Present
"DS-50"
50kg active volume
first physics results

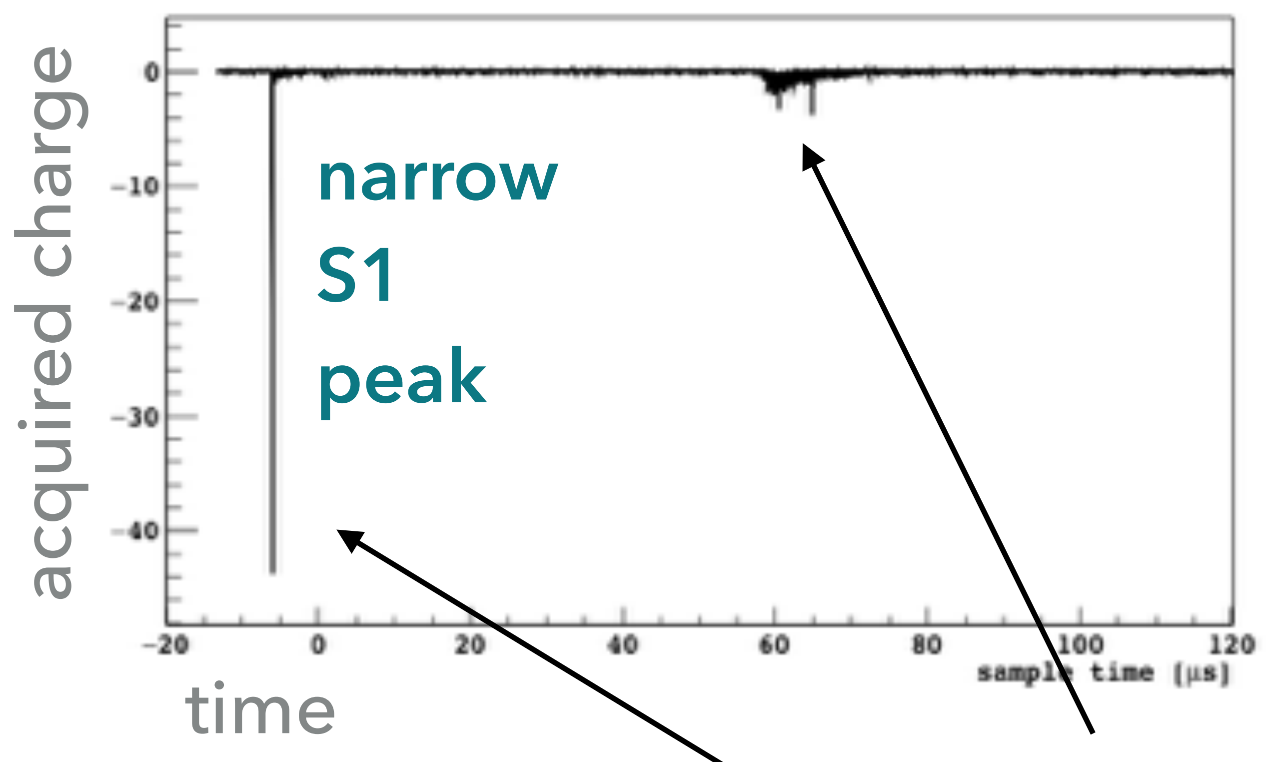
2019 - ?
"DS-20k"
20Mg active volume
touches neutrino floor
(1 or 2 expected events)

APC, Université Paris Diderot, CNRS/IN2P3 | Gran Sasso Science Institute (GSSI) | Laboratori Nazionali del Gran Sasso (LNGS) | Augustana University | Belgorod National Research University | Black Hills State University | Budker Institute of Nuclear Physics | Instituto Nazionale di Fisica Nucleare (INFN) | Universidade Estadual de Campinas | Università degli Studi | Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT) | I(NCD)TIM | University of California | Joint Institute for Nuclear Research (JINR) | ETHZ, Swiss Federal Institute of Technology | Fondazione Bruno Kessler (FBK) | Fermi National Accelerator Laboratory (FNAL) | Fort Lewis College | University of Hawai'i | Institute of High Energy Physics (IHEP) | IPHC, Université de Strasbourg, CNRS/IN2P3 | Institute for Nuclear Research, National Academy of Sciences of Ukraine | Smoluchowski Institute of Physics, Jagiellonian University | National Research Centre Kurchatov Institute | Lawrence Livermore National Laboratory (LLNL) | LPNHE Paris, Université Pierre et Marie Curie, Université Paris Diderot | Laboratorio Subterráneo de Canfranc | National Research Nuclear University MEPhI | Politecnico di Milano | Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University | Novosibirsk State University | St. Petersburg Nuclear Physics Institute, NRC Kurchatov Institute | Università di Pisa | Pacific Northwest National Laboratory (PNNL) | Princeton University | Università di Roma (Roma Uno) | SLAC National Accelerator Laboratory | Temple University | TIFPA, Trento Institute for Fundamental Physics and Applications | Amherst Center for Fundamental Interactions, University of Massachusetts | University of Crete | Instituto de Física, Universidade de São Paulo | Virginia Tech

THE TIME-PROJECTION CHAMBER (TPC)

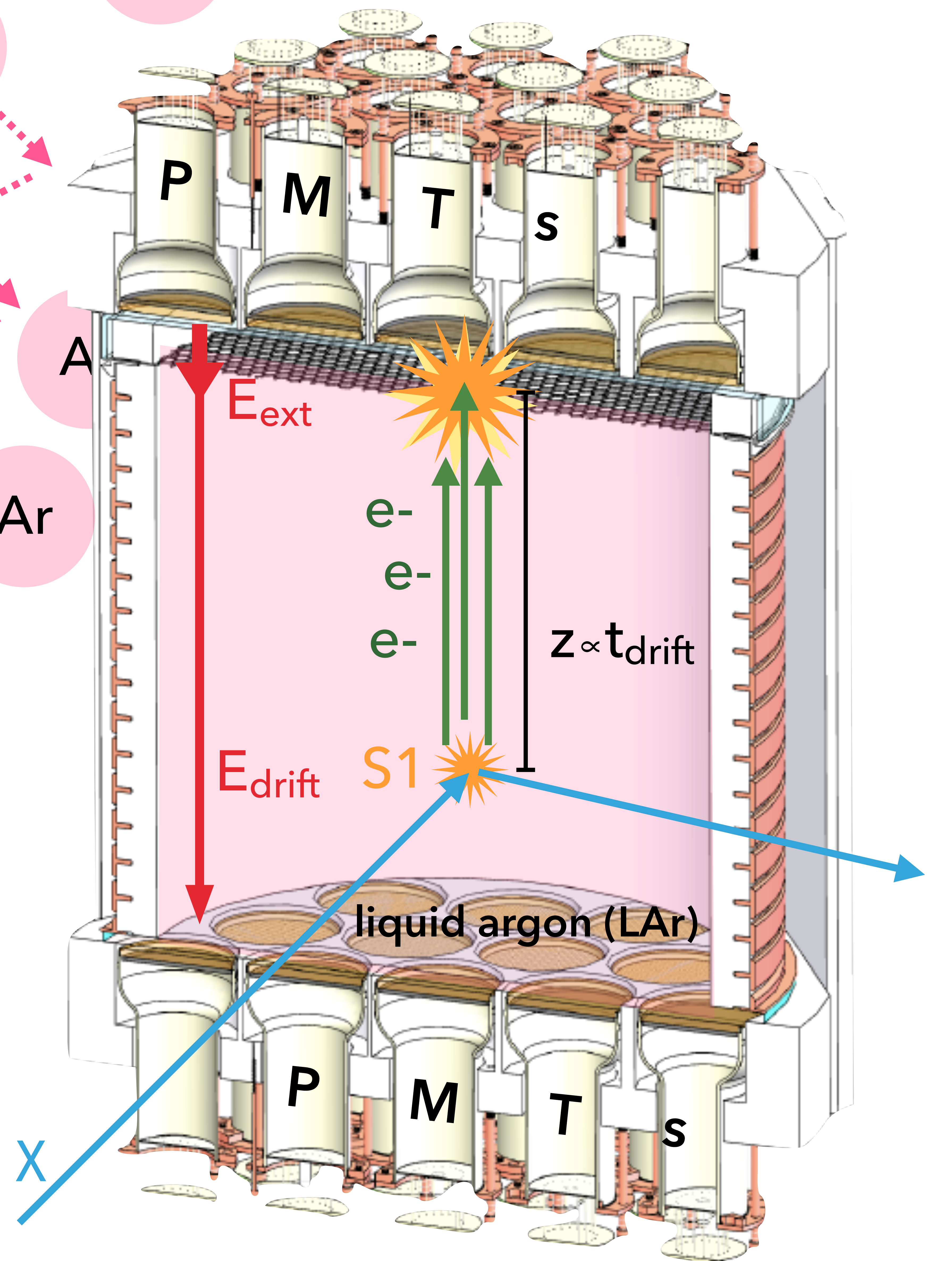






$\int(S1) \ll \int(S2)$

$\int(S1) \leq \int(S2)$



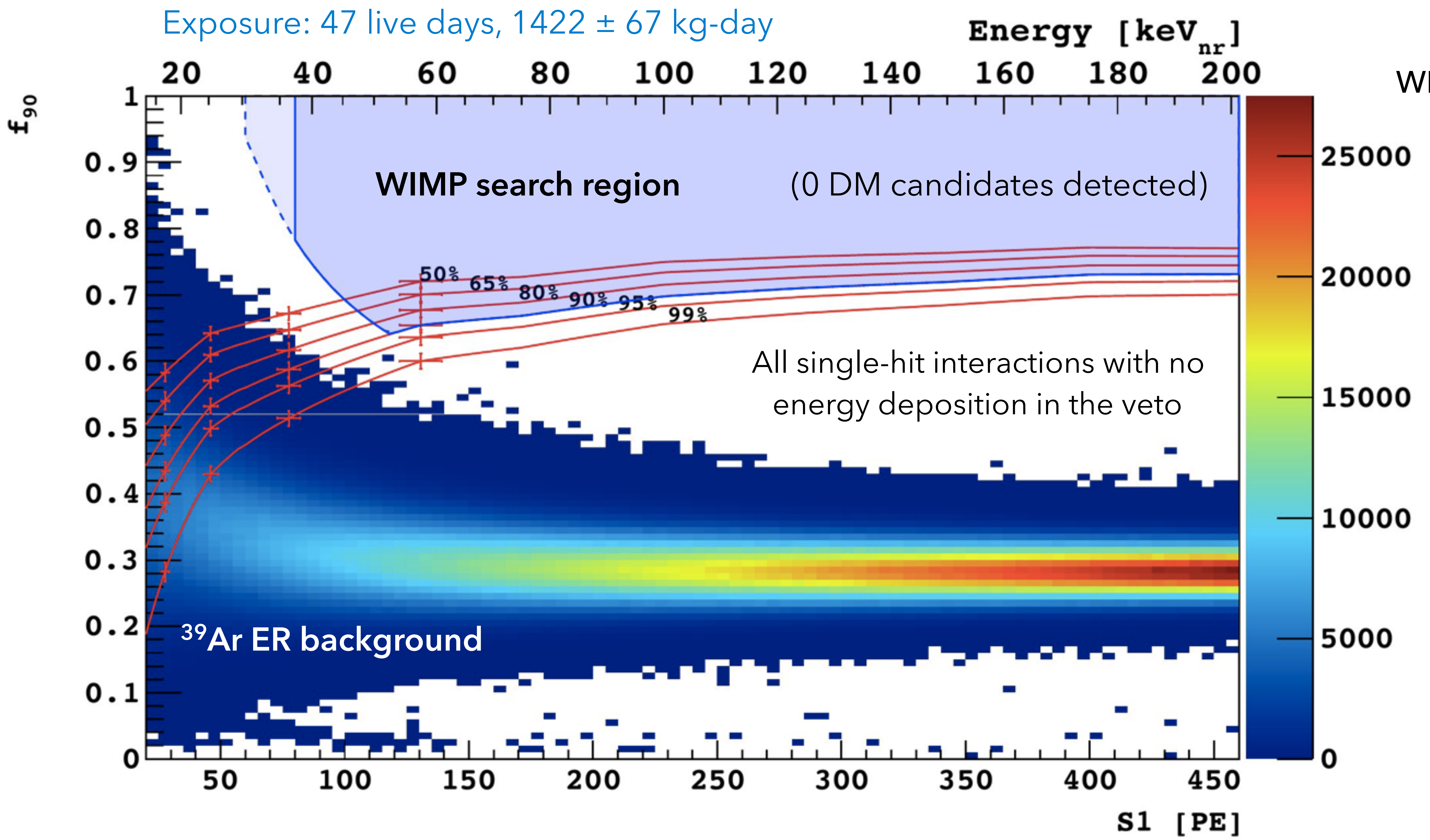
S2/S1 ratio and Pulse Shape Discrimination (PSD)
WIMPs will generate nuclear recoils (NRs)

* usu. caused by incident γ's or 39Ar β- decay, not incident e-'s

PSD IN DARKSIDE-50 — FIRST RESULTS (9 APRIL 2015)

First results used atmospheric argon (AAr), which contains ^{39}Ar – a cosmogenic isotope of argon (τ = 269y) in trace amounts.

…more recent results use underground argon (UAr) extracted from the Kinder Morgan CO_2 source in Cortez, CO, USA.

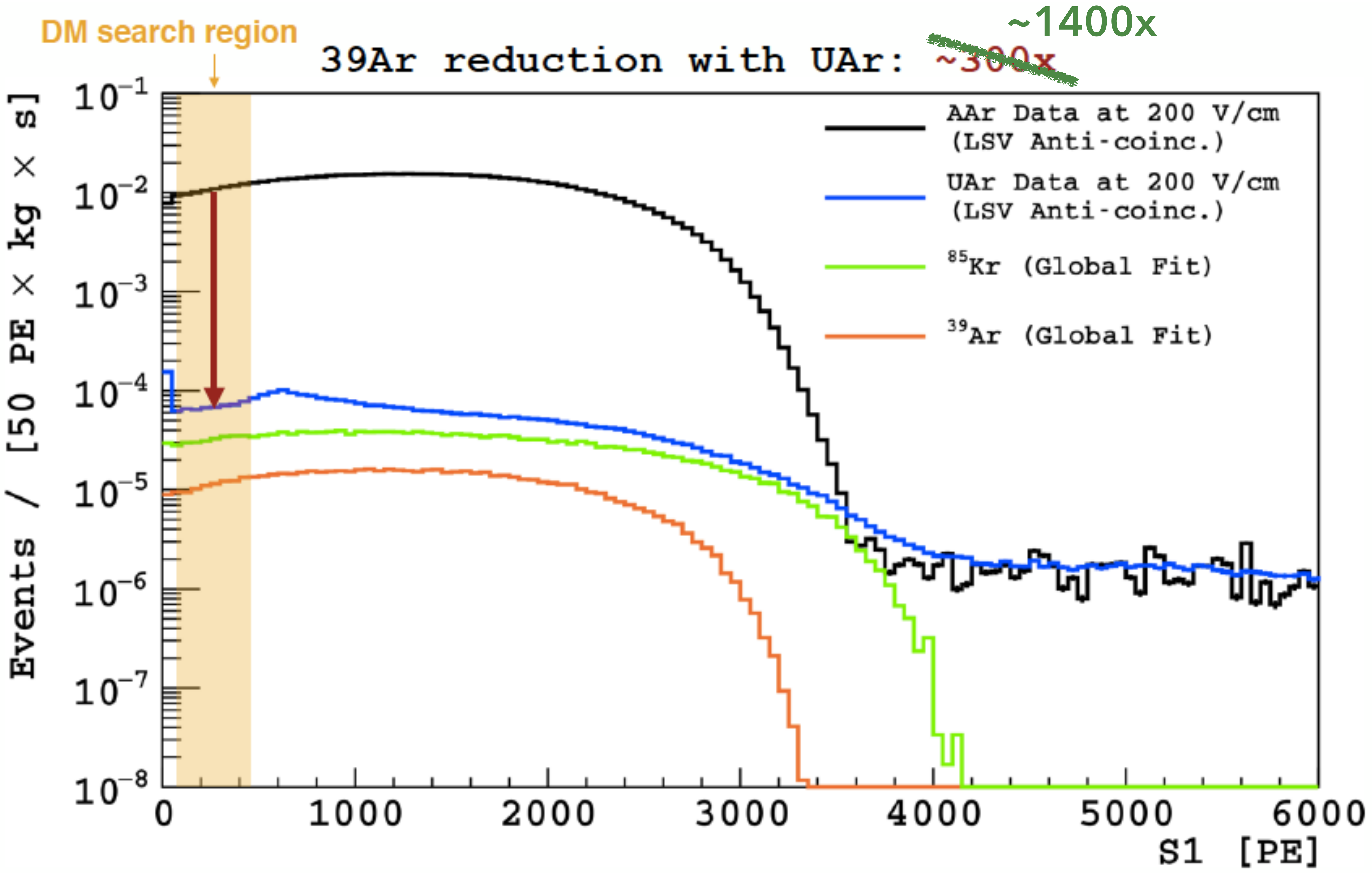


Discrimination power of DarkSide-50:

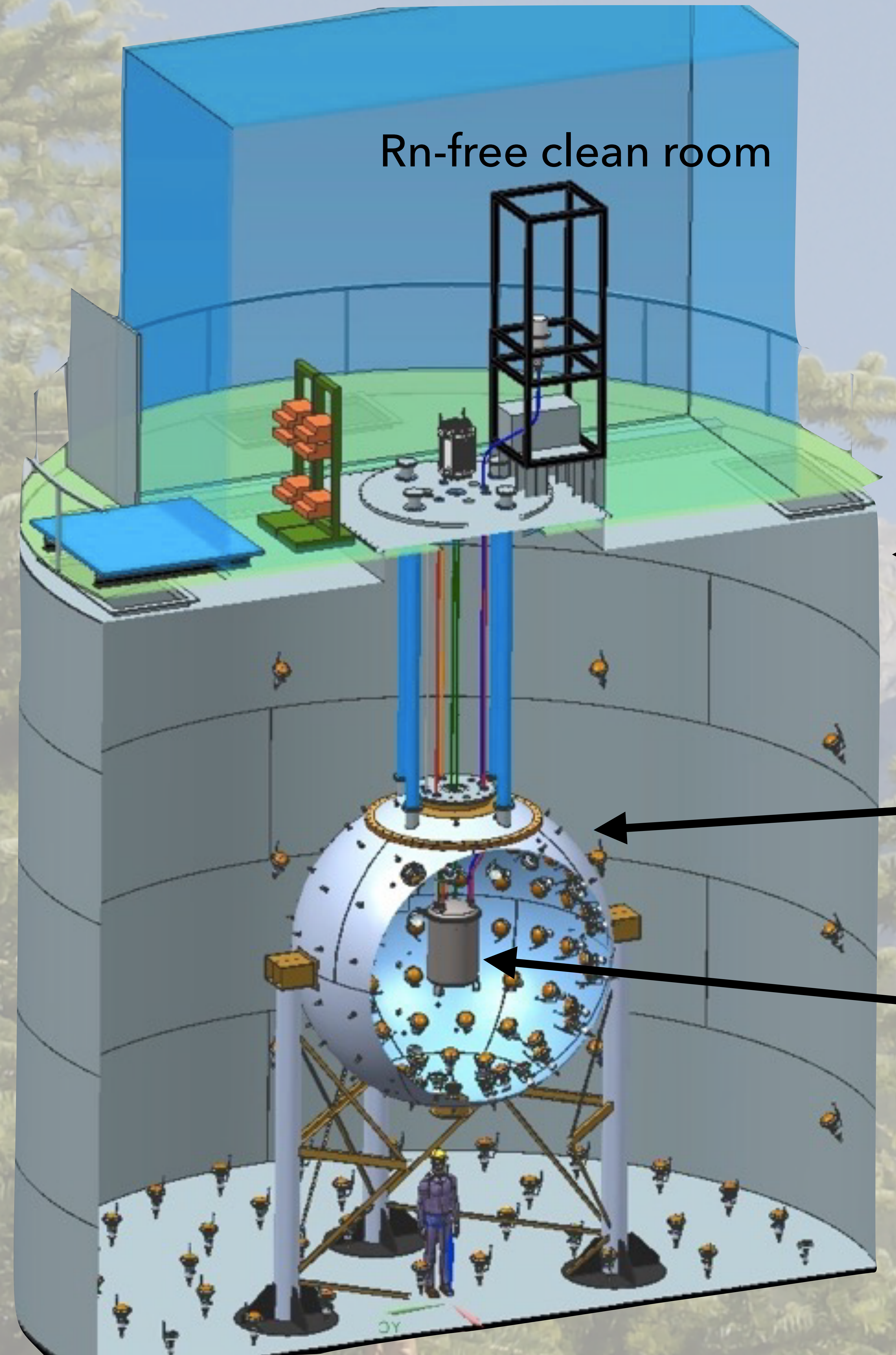
15M ER events in WIMP energy range… 0 NR events.

Underground argon (UAr) reduces this background even further…

UNDERGROUND ARGON



BACKGROUND REJECTION IN DS-50 (1/2) — ACTIVE AND PASSIVE VETOES



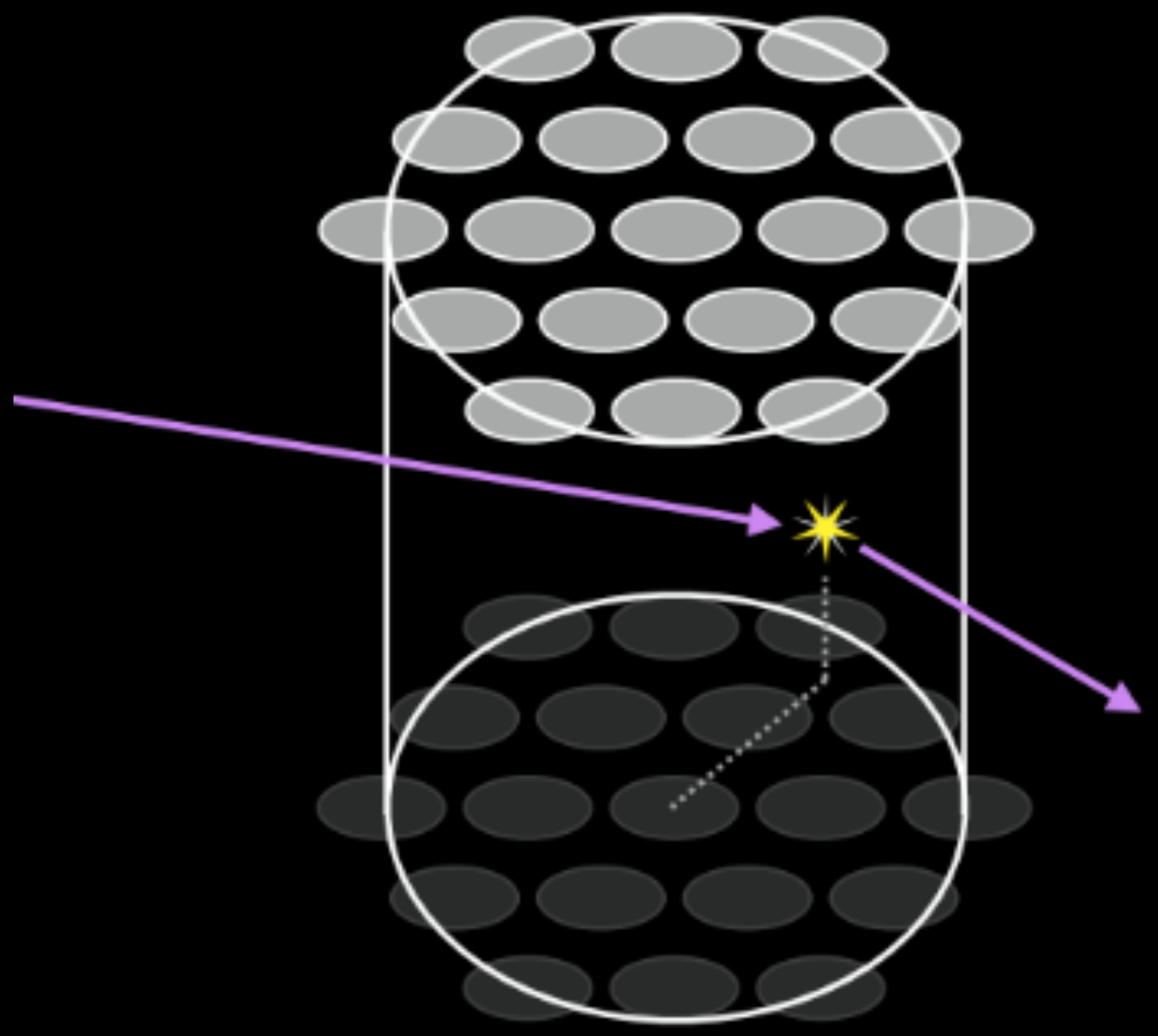
Corno Grande of the Gran Sasso massif (pictured) provides 3800 m.w.e. passive shielding against cosmic rays

11m-diameter, 10m-tall Water Čerenkov Detector (WCD) provides active shielding against γ's, n's, μ's

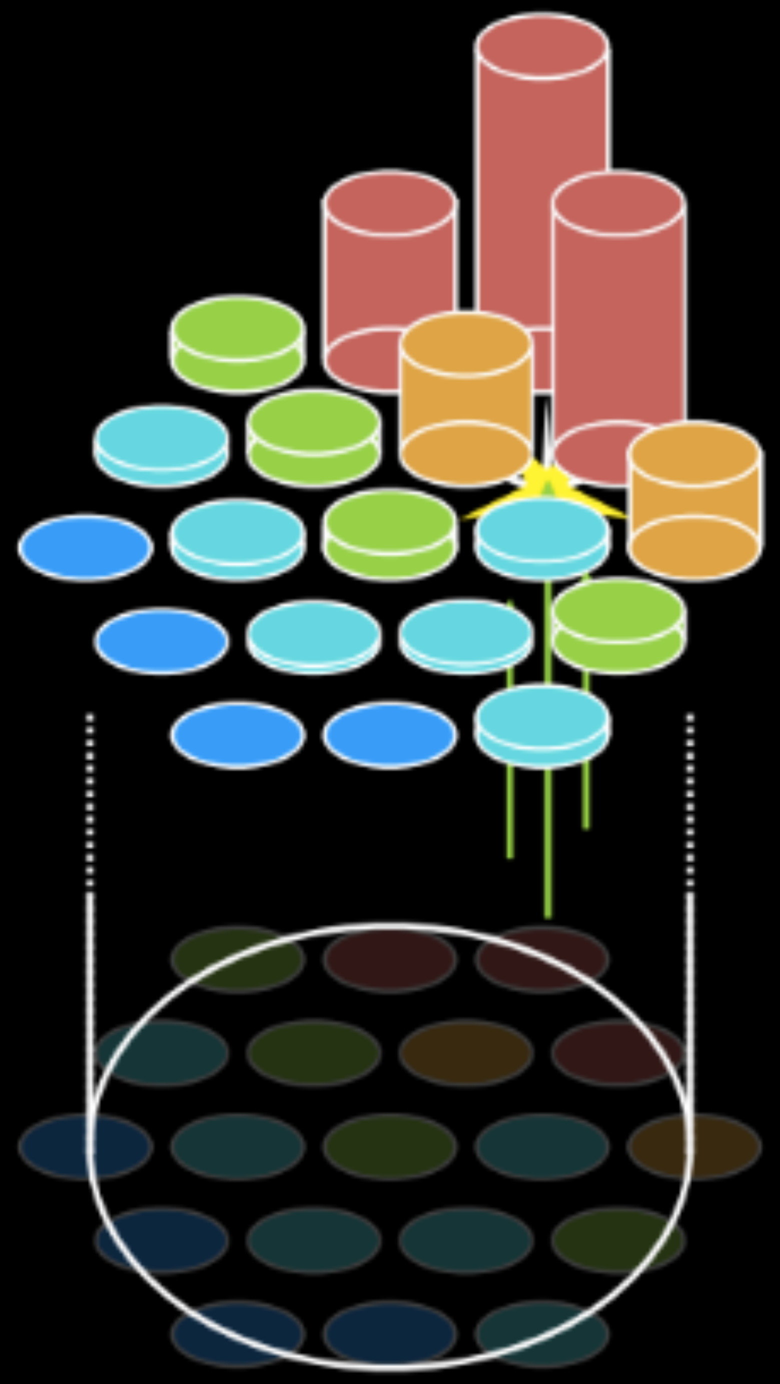
4m-diameter borated Liquid Scintillator Veto (LSV) provides additional active shielding against γ's and n's

…these all surround the inner detector, the Time Projection Chamber (TPC)

BACKGROUND REJECTION IN DS-50 (2/2) — 3D-POSITION RECONSTRUCTION



particle interacts in LAr
creates S1 light
ionizes Ar atoms
generates free electrons

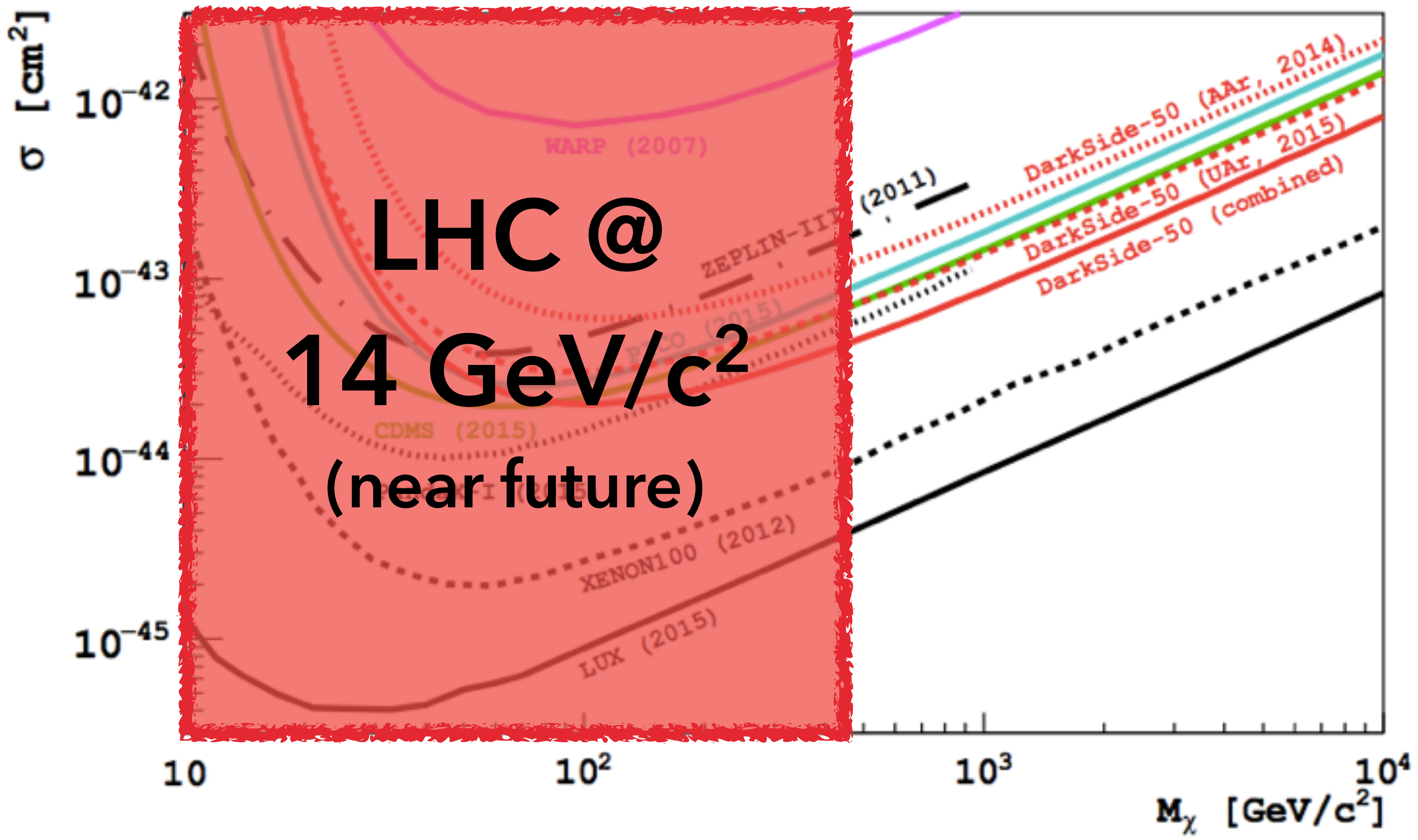


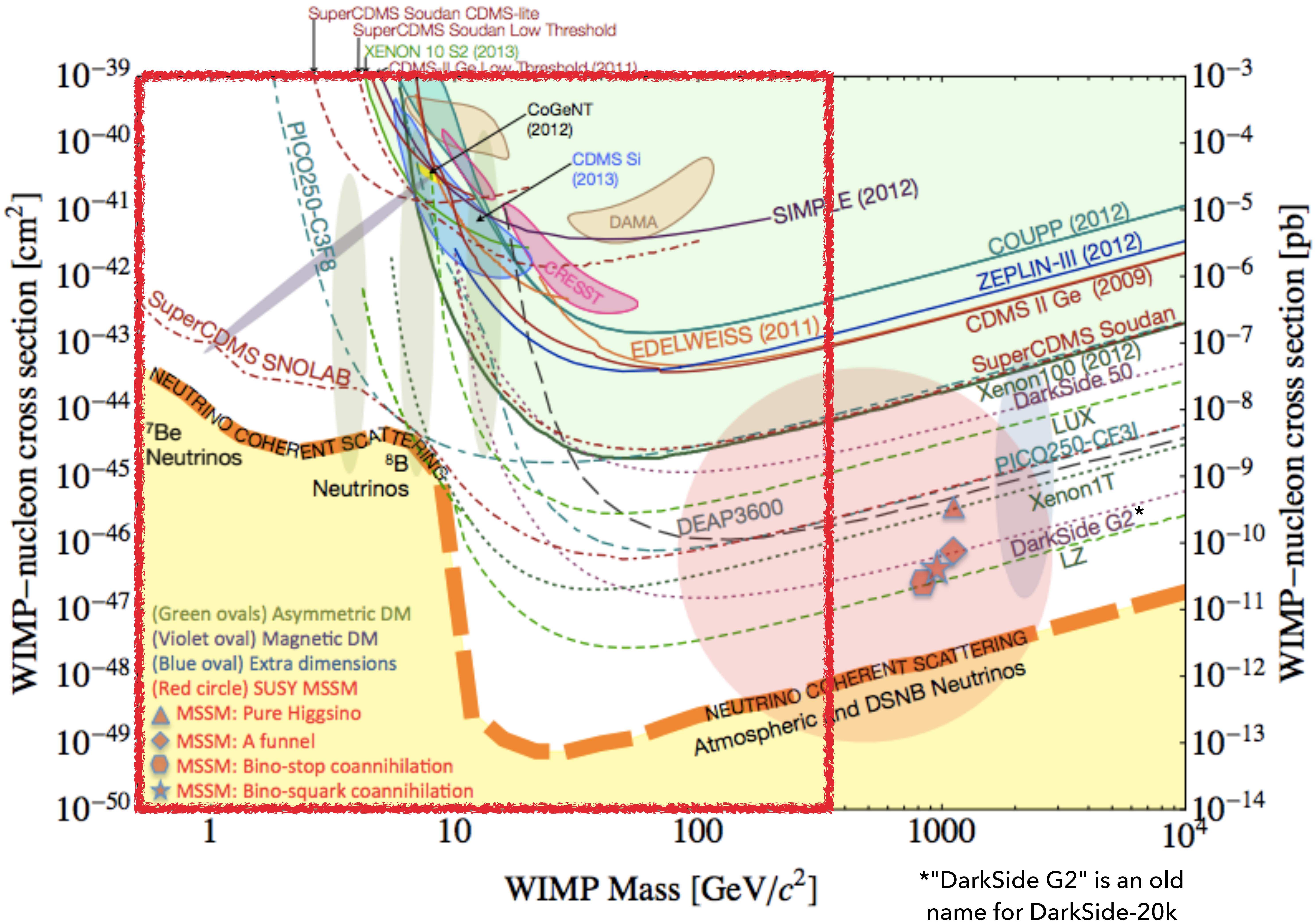
because of applied E
field, electrons drift
toward anode, generate
S2 light in gAr

0.05 0.13 0.20
0.03 0.05 0.08 0.18
0.00 0.03 0.04 0.03 0.05
0.01 0.02 0.02 0.04
0.00 0.01 0.03

fraction of S2 light is a
function of event XY
(transverse) position

STATE OF SPIN-INDEPENDENT DIRECT DARK MATTER DETECTION





*"DarkSide G2" is an old name for DarkSide-20k

(top plot highlights DS results; left plot legend is below)

solid lines: WIMP-nucleon spin-independent cross section limits

shaded closed contours: hints of WIMP signals

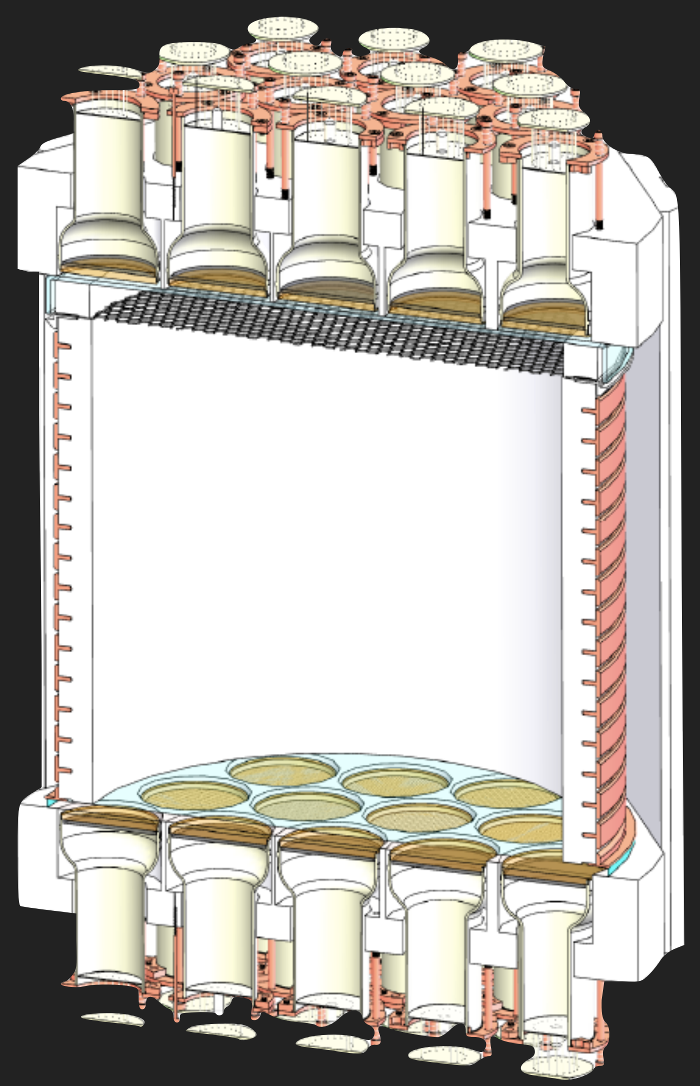
dot and dot-dash curves: projections for direct detection experiments coming online over the next decade

big orange dashed curve: "neutrino floor"; where coherent scattering of 8B solar neutrinos, atmospheric neutrinos, and diffuse supernova neutrinos with nuclei will become a background for direct detection experiments

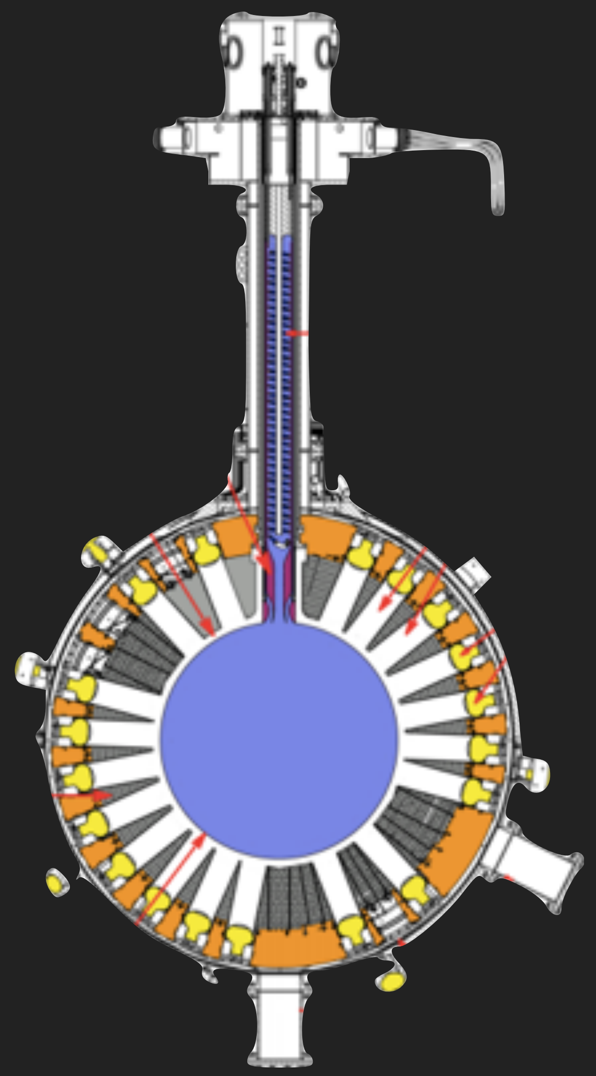
other shaded regions and markers: predictions from various models for different DM candidates

PRESENT AND FUTURE DETECTORS (NOT TO SCALE)

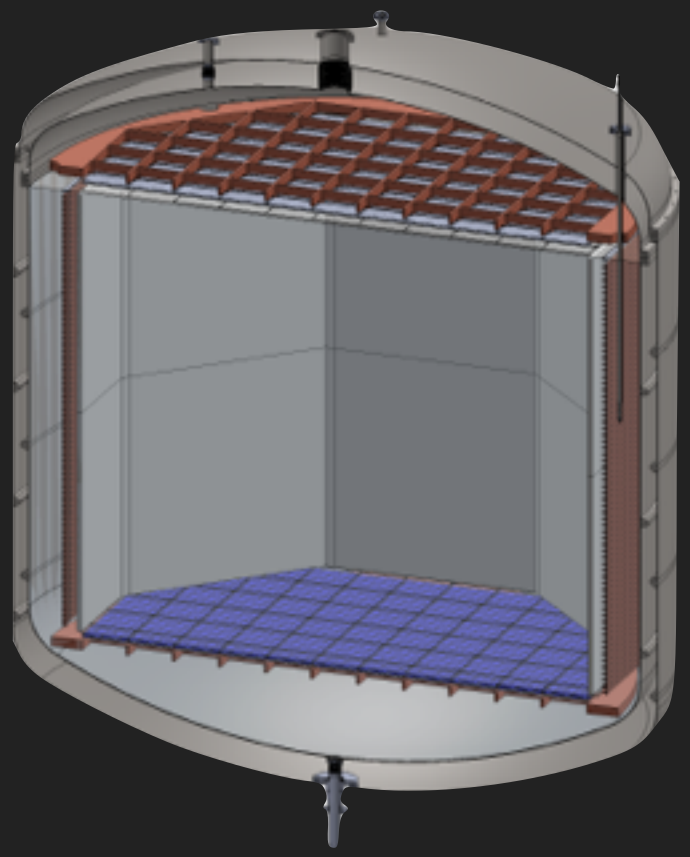
also Panda X, DARWIN, ArDM, SuperCDMS…too many to list!
See http://bit.ly/2eQwmsJ for a more thorough overview



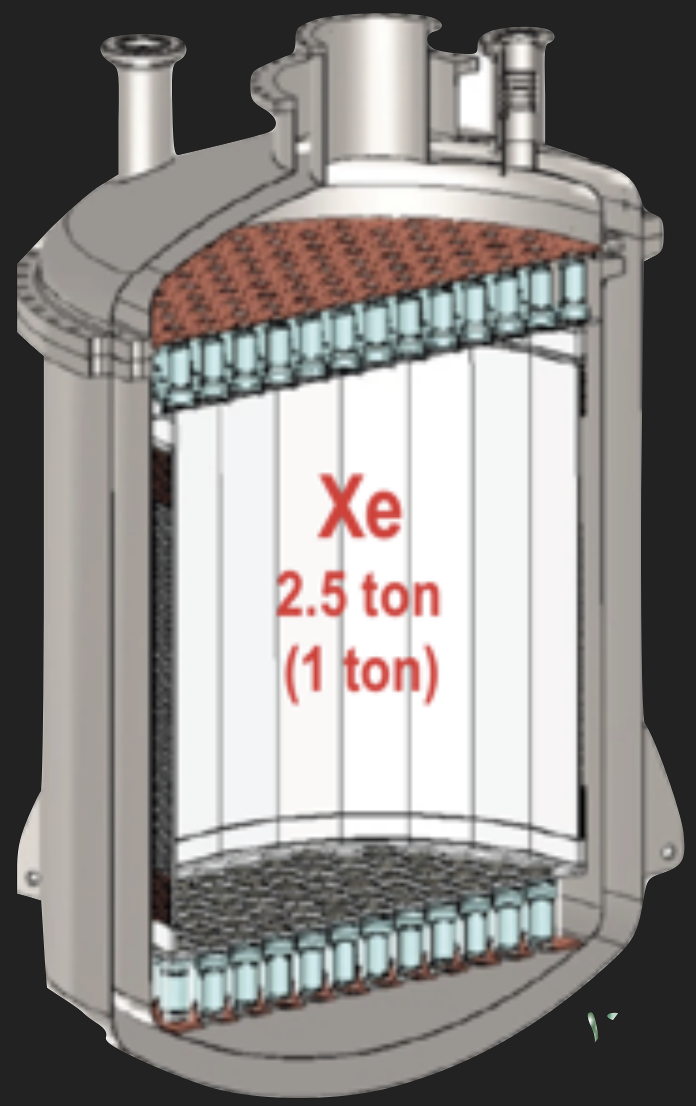
DarkSide-50
0.05Mg target Ar
σ ~ 10^{-44}
online **NOW**



DEAP-3600
1Mg target Ar
σ ~ 10^{-46}
online **NOW**

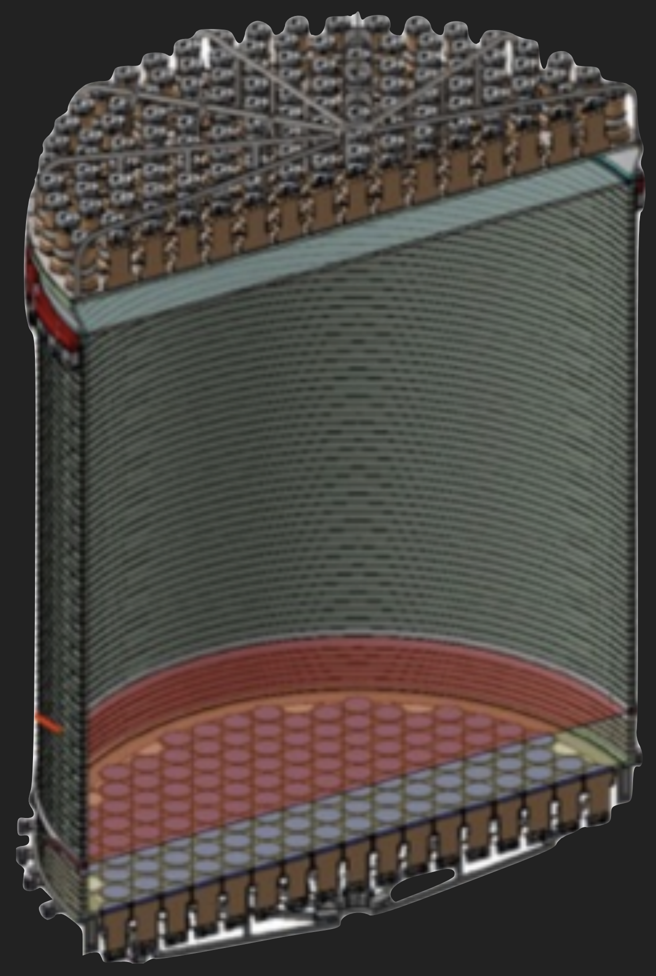


DarkSide-20k
20Mg target Ar
σ ~ 10^{-47}
online by 2021



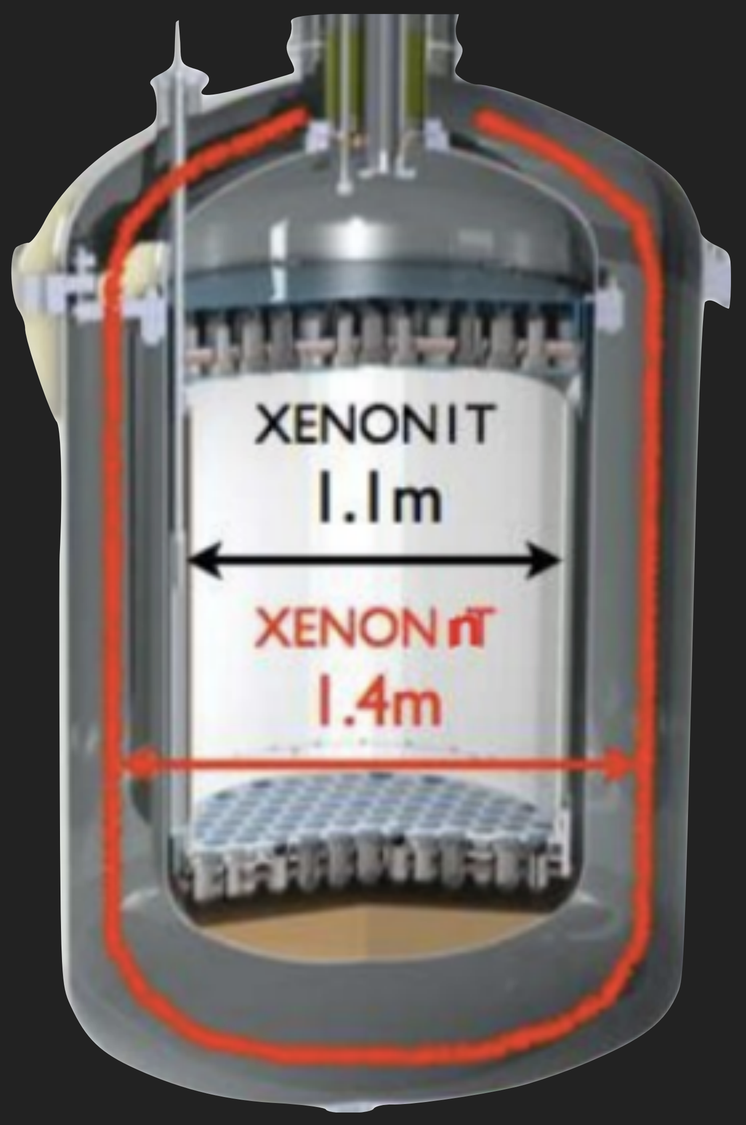
XENON-1T
1Mg target Xe
σ ~ 10^{-47}
online **NOW**

Expected physics results by 2018



LZ
7Mg total Xe
σ ~ 10^{-47}
online by 2019

1000-day WIMP search 2019-2021



Xenon-nT
7Mg total Xe
σ ~ 10^{-48}
online by 2020

1st gen. detectors — 2nd gen. detectors — 3rd gen. detectors

Thank You!

ANDREW W WATSON

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awwatson.com

BACKUP SLIDES

BACKUP: ELECTRON RECOILS VS. NUCLEAR RECOILS

- Electron Recoils (ERs)
  - e-'s recoil many times, striking many Ar nuclei
  - they leave a long, diffuse track of excited and ionized Ar nuclei
- Nuclear Recoils (NRs)
  - n's recoil just once or a few times, striking few Ar's
  - they leave a short, dense track of excited and ionized Ar nuclei

singlet/triplet ratio depends on ionization density

Two excitation channels…

$$Ar^* + Ar \rightarrow Ar_2^*$$
$$Ar_2^* \rightarrow 2Ar + h\nu$$

Weakly bound dimer ("exciton")

VUV scintillation (128nm)

$$Ar^+ + Ar \rightarrow Ar_2^+$$
$$Ar_2^+ + e^- \rightarrow Ar^{**} + Ar$$
$$Ar^{**} \rightarrow Ar^* + \text{heat}$$
$$Ar^* + Ar \rightarrow Ar_2^*$$
$$Ar_2^* \rightarrow 2Ar + h\nu$$

Exciton can be in either singlet or triplet state:

- Singlet state has decay time τ = 7 ns ("fast")
- Triplet state has decay time τ = 1.6 μs ("slow")

Singlet/Triplet ratio differs for ER vs. NR

- ~0.3 for ER
- ~3.0 for NR

(Exact reason *why* this is the case is unknown.)

BACKUP: PSD ARGON VS. XENON

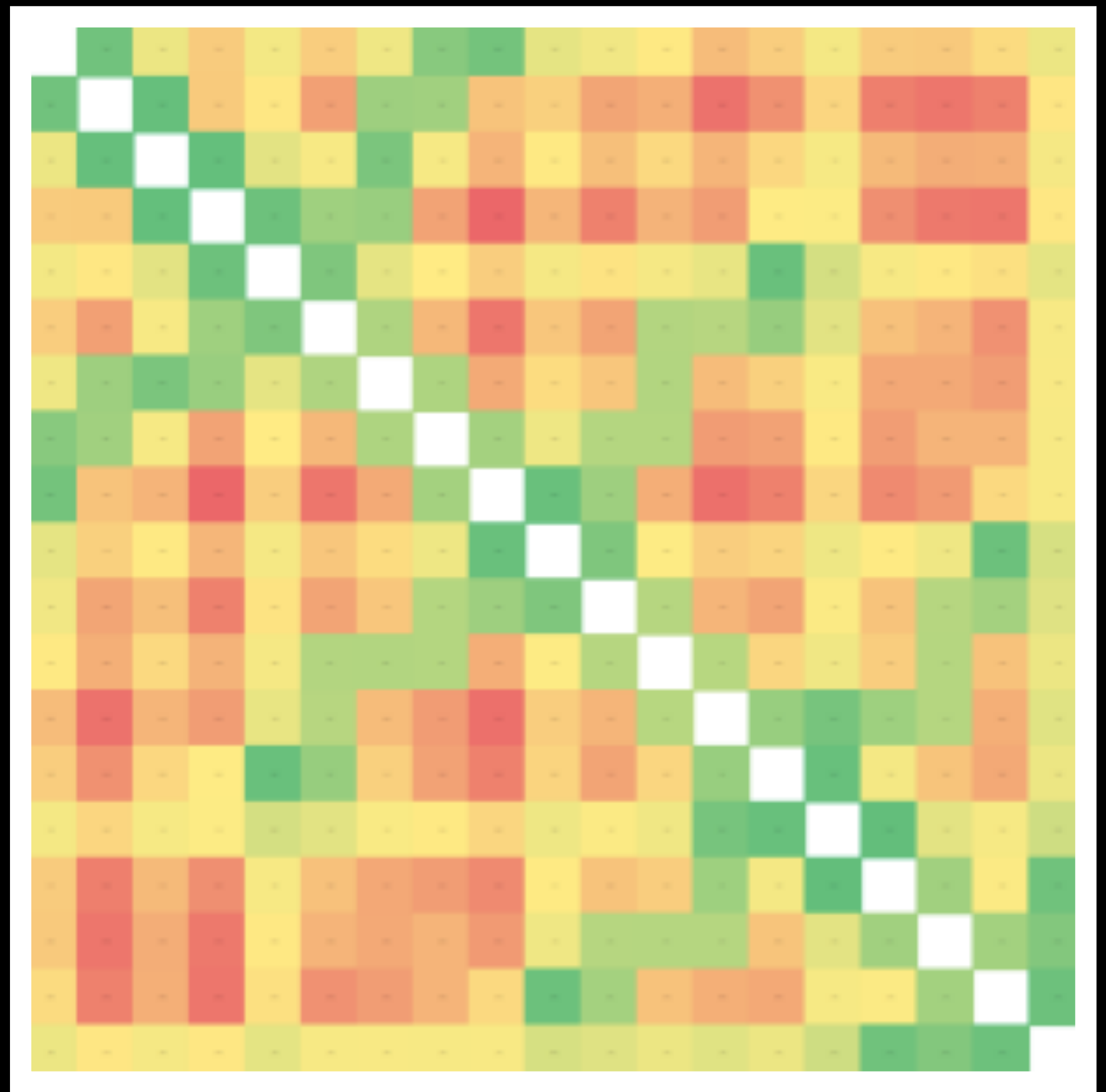
- (see previous slide first)
- Xe also has two excitation channels
    - "fast" component: 4.3 ns
    - "slow" component: 22 ns
- Very small difference in decay times makes PSD impractical
- Xenon-based experiments generally use S2/S1 ratio instead of PSD, giving a smaller (10^3 vs. 10^7) discrimination power

BACKUP: PCA-MDF XY RECONSTRUCTION IN DARKSIDE-50

Principal Component Analysis / Multi-Dimensional Fitting

Principal Component Analysis

1. Generate covariance matrix
2. Find eigenvalues/vectors
3. Coordinate transformation

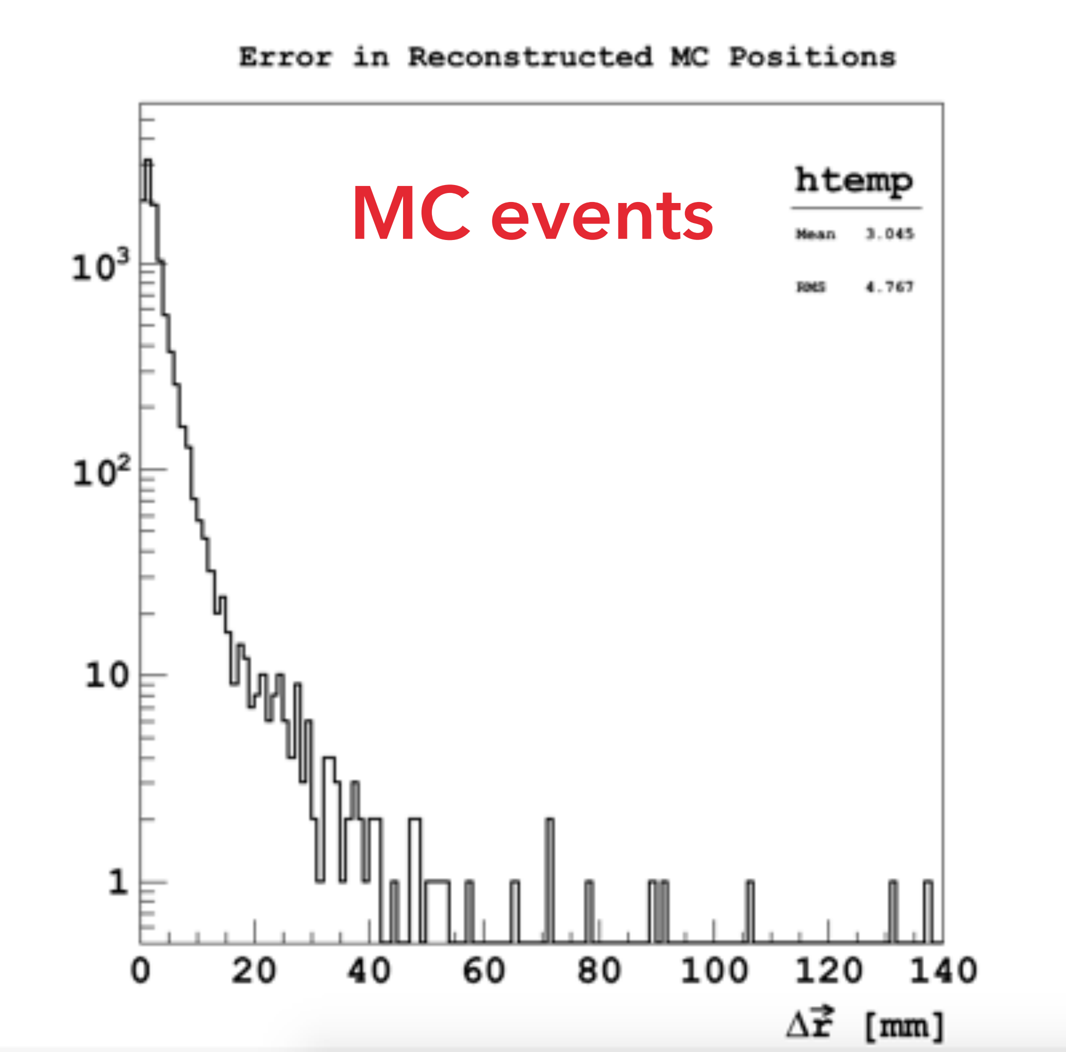


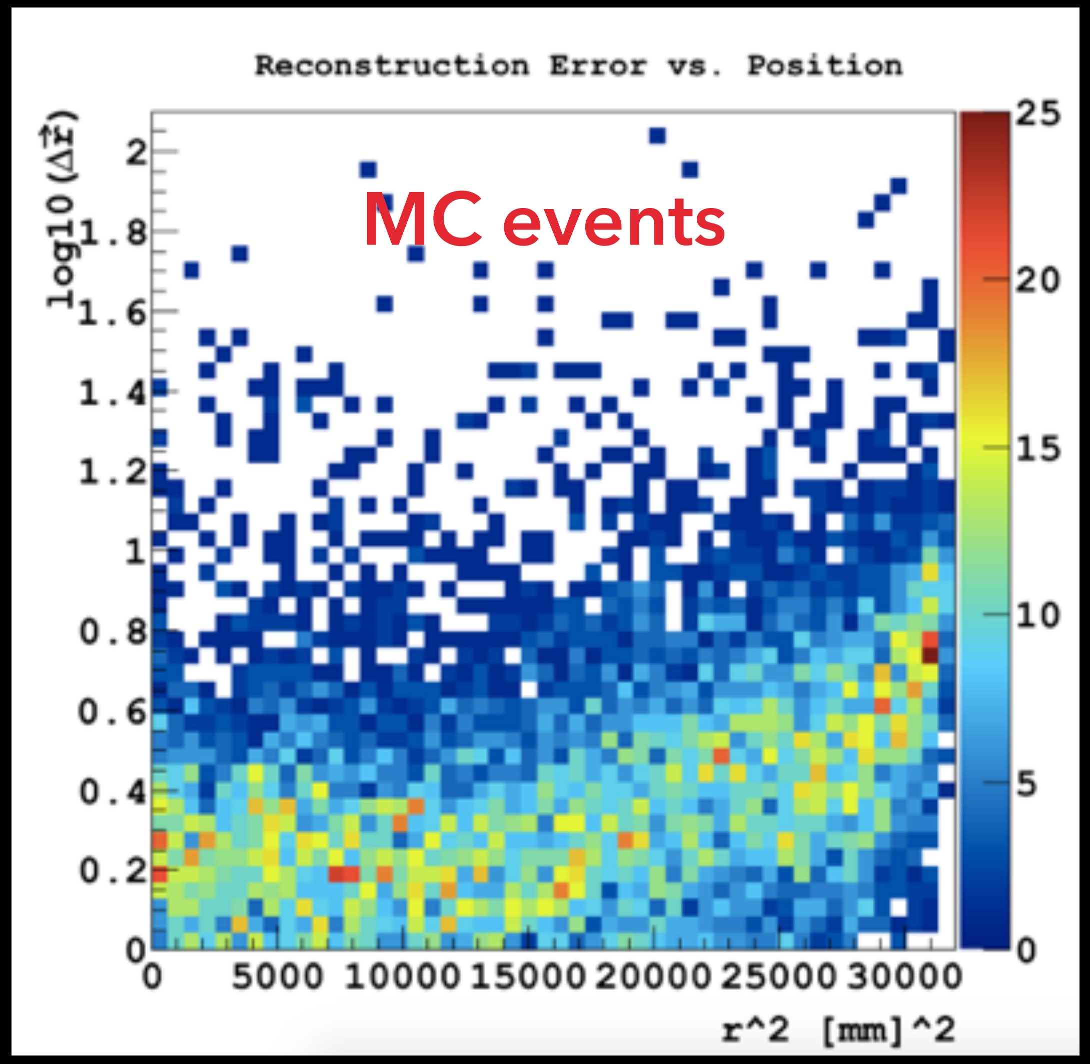
Monte Carlo: generate MC events, get S2 fractions on anode PMTs → do PCA, find most significant principal components → do MDF on principal components → generate fitting functions

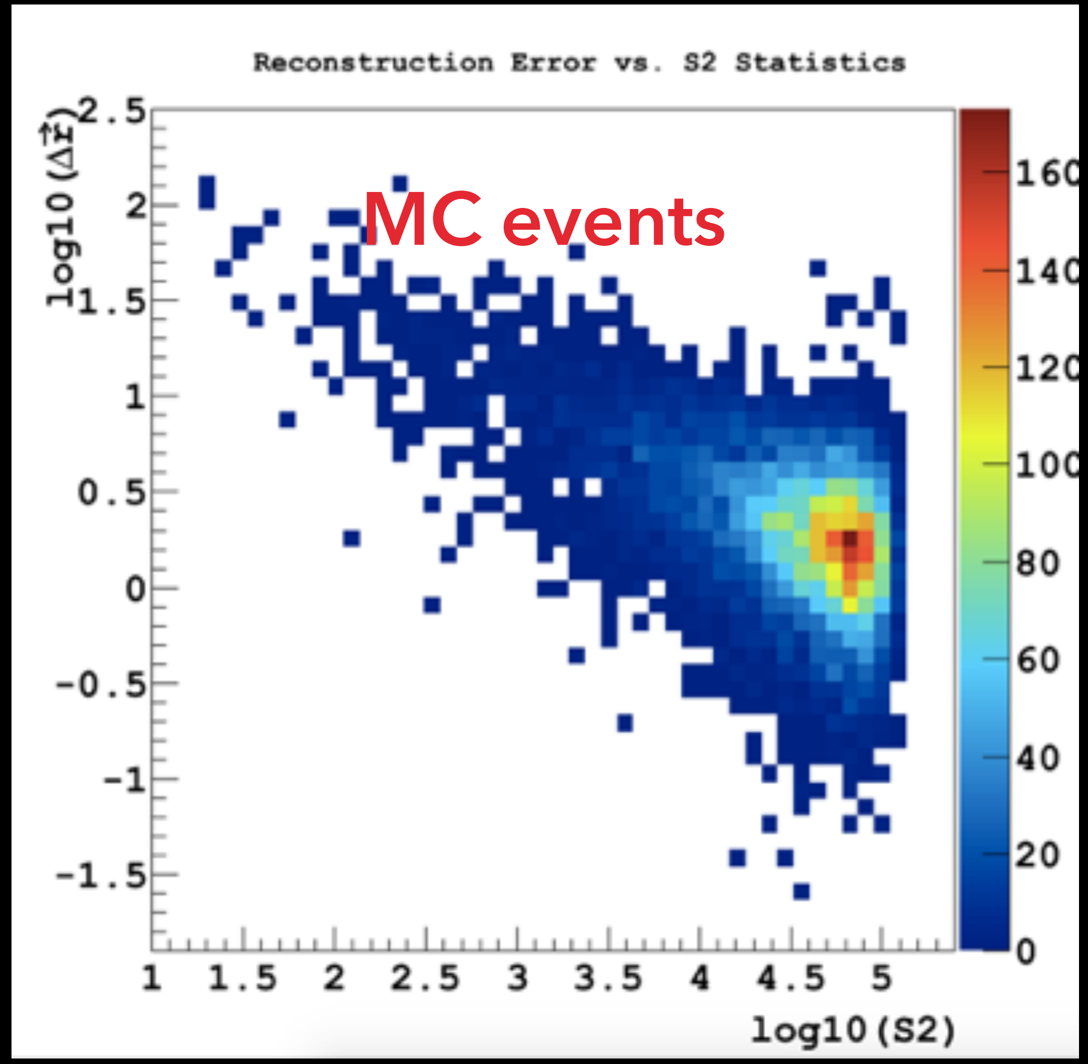
do PCA, find most significant principal components ↓ convert feature-space variables to pattern-space (PC's)

generate fitting functions ↙ use MC MDF to move from PC's to XY positions

Data: get event S2 fractions on anode PMTs → convert feature-space variables to pattern-space (PC's) → use MC MDF to move from PC's to XY positions → **reconstructed XY positions!**







BACKUP: NEUTRINO DETECTION EXPERIMENTS?

Why can't current neutrino detection experiments, with their huge liquid argon active volumes, detect DM?

1. **Energy Scale** – large neutrino-detection experiments generally are sensitive only to energy deposits O(MeV), while DM should deposit only a few tens of keV. Neutrino experiments only collect charge, while dual-phase TPCs detect both charge and scintillation – about 40 photons are generated for each keV of energy deposited in the DarkSide liquid volume.

2. **Purity** – The DarkSide Collaboration currently holds the world's supply of UAr, which is essential to eliminating the pervasive ^{39}Ar ER background in a liquid-argon-based DM detection experiment.